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THESIS

ACOUSTIC UNDERWATER NAVIGATION OF THE PHOENIX AUTONOMOUS UNDERWATER VEHICLE USING THE DIVETRACKER SYSTEM

by

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March, 1996

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ACOUSTIC UNDERWATER NAVIGATION OF THE PHOENIX AUTONOMOUS UNDERWATER VEHICLE USING THE DIVETRACKER SYSTEM

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ABSTRACT

Autonomous Underwater Vehicles (AUVs) require a navigation system in order to conduct useful functions. This research was an experimental investigation of the commercial DiveTracker underwater acoustic navigation system used onboard the NPS Phoenix AUV. Tests conducted with the DiveTracker system proved that the system could be used successfully in AUV navigation while submerged and revealed that more precise positioning could be obtained through postconditioning of the DiveTracker output ranges, rather than prefiltering.

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I. INTRODUCTION

A. THE NEED FOR MINE RECONNAISSANCE

During the Korean War a United States Navy armada of 250 ships and 50,000 Marines were delayed in assaulting the Korean port of Wonsan through the failure to recognize the importance of mine warfare. The Amphibious Task Force Commander remarked "We have lost control of the seas to a nation without a Navy..." , [Reference 1]. The most serious enemy inflicted damage to U.S. Navy since World War II has been caused by undetected mines in the Persian Gulf. *USS Samuel B. Roberts* (FF-58), *USS Tripoli* (LPHG-10)and *USS Princeton* (CG-59), unknowingly steamed into Iraqi mine fields. During the Gulf War, *USS Tripoli* was the flagship of the Navy's Mine Countermeasures Group and was incharge of reconnoitering and clearing a path through the mine fields, [Reference 2]. A recent Chief of Naval Operations White Paper has called for increased efforts in mine warfare, including research and development programs, [Reference 3].

B. AUV APPLICATION

Mine hunting in the shallow water zone (10 to 40 feet) presents unique challenges to the U.S. Navy. For maximum flexibility the mine countermeasure efforts should be covert, cost effective and relatively quick, [Reference 1]. Current MCM efforts that involve both ships and helicopters do not have a covert capability and are highly susceptible to shore based missile batteries. Marine mammal systems and special forces are capable of operating covertly. However they are scarce resources that require extensive training pipelines, [Reference 4]. The marine mammals are limited to MCM efforts in water depths of forty feet and greater and require onsite

handling. The Commander, Mine Warfare Command, has recently stated the need for development of Autonomous Ocean Network employing Autonomous Reconnaissance Vehicles (ARV) and Small Neutralizer Robots. Today, the AUV technology exists to engineer and deploy such mine reconnaissance vehicles capable of operating clandestinely in the shallow water and very shallow water zone.

C. SCOPE OF THESIS

One of the key engineering problems facing development and greater utilization of autonomous vehicles, underwater navigation, communications and control are high on the list. Underwater navigation is accomplished in submarine using expensive and large inertial systems. Other dead reconing techniques include the use of doppler sensors for speed over ground combined with a compass or directional gyroscope heading reference. Alternatively, acoustic beacons may be used but are expensive and usually provide position only to a mother ship.

The primary focus of this thesis was to determine the viability of the DiveTracker system in establishing the lateral position of the Phoenix AUV while operating submerged in a salt water environment. Specific objectives were to determine the error associated with DiveTracker range values and to determine the best method of filtering the position data.

Chapter II contains a discussion of acoustic navigation and Phoenix AUV employment concept. Chapters III and IV describe the DiveTracker system and Phoenix AUV in detail. Chapter V describes the experimental procedure completed. Chapter VI presents the Kalman filter used in data smoothing, the experimental results and data analysis. Conclusions and recommendations are made in Chapter VII. Pertinent computer

files are given in Appendices A and B. Figures are presented at the end of each chapter as applicable.

II. ACOUSTIC UNDERWATER NAVIGATION

A. LIMITATIONS OF GPS/INS

For AUV navigation the use of the Global Positioning System requires that the vehicle be at the surface in order to expose an antenna. This removes the vehicle sonar from the most favorable depth for sonar search. Use of an antenna buoy tethered to the vehicle imposes an unacceptable drag penalty on the vehicle. An inertial navigation system (INS) adds weight, size, and power requirement penalties. Small inertial systems are susceptible to position and heading drift. As more accurate inertial system are used the cost, size and power requirements increase rapidly. Current acoustic tracking systems offer a low power, small sized package suitable for underwater vehicle navigation. One such system is the DiveTracker system manufactured by Desert Star Systems. This navigation system is small in size with low power requirements and provided acoustic navigation to the submerged Phoenix AUV. DiveTracker uses fixed acoustic transducers to establish a reference baseline for navigation, and therefore minimized drift errors.

B. ACOUSTIC BASELINE NAVIGATION

An acoustic navigation system is one in which a vehicle determines its location by measuring the range to a fixed acoustic array. The advantage of such a system are minimal hardware installation, minimal use of vehicle power, small size, and the incorporation of acoustic modem for data transmission. The system installed on the Phoenix AUV uses the DiveTracker system developed by Desert Star.

In acoustic navigation systems, range is not measured directly. The time difference between transmitted and

received sonar pulses or 'pings' are converted to range. To determine the range from a fixed array element the vehicle measures the time difference between a transmitted ping and received reply ping. The range equation is:

$$R = \frac{t_{received} - t_{sent}}{c}. \tag{1}$$

Unlike hyperbolic systems such as Loran or Omega radio navigation systems, the DiveTracker system measures actual received time not time difference between two or more array elements. The advantage of such a system is that an exact global time standard is not necessary. Only the time difference between pings must be measured accurately. The range give a coordinate corresponding to a arc of constant range from corresponding the array element. The crossing to two or more range arcs gives the vehicle location in an cartesian coordinate system. The coordinate system used by the Phoenix vehicle is a right handed system defined as follows:

X-axis points North
Y-axis points East
Z-axis points Down

The Phoenix AUV system has been developed to date using a two element array which will be referred to as a "short baseline system", (SBL). The two element array yields two X coordinate solution values and give a true and 'ghost' position. Therefore it is necessary to know on which side of the array baseline the vehicle is operating.. A three element array would provide a third range arc and give the system a single solution automatically, but with added expense and complexity.

C. RANGE TO CARTESIAN COORDINATE CONVERSION

In the established coordinate system (see Figure 1), one array transducer is located at the origin, and the second at a known location (X_0, Y_0). X and Y coordinates are determined from using the following equations:

$$F_1(X,Y,Z,R1) = X^2 + Y^2 + (Z - Z_{01})^2 - R1^2 = 0 \tag{2}$$

$$F_2(X,Y,Z,R1) = (X - X_{02})^2 + (Y - Y_{02})^2 + (Z - Z_{02})^2 - R2^2 = 0 \tag{3}$$

where

Z_{01} = Surface Station 1 Depth

X_{02} = Surface Station 2 X coordinate

Y_{02} = Surface Station 2 Y coordinate

Z_{02} = Surface Station 2 Depth

The Z coordinate is given by vehicle depth as measured from the onboard depth sensor. These equations then can be solved either analytically or numerically and are computed to yield current position (X,Y,Z). For operations with the transducers and vehicle near the same horizontal plane the problem reduces from a spherical solution to a cylindrical solution.

The accuracy of the cylindrical solution differs from the hyperbolic navigation. Solution error sensitivity is studied by linearizing equations (2) and (3), and defining the Jacobian of the range equations as F(y,x) as:

$$J = \begin{bmatrix} \dfrac{\partial F_1}{\partial y} & \dfrac{\partial F_1}{\partial x} \\ \dfrac{\partial F_2}{\partial y} & \dfrac{\partial F_2}{\partial x} \end{bmatrix} = \begin{bmatrix} 2y & 2x \\ 2(y - y_0) & 2(x - x_0) \end{bmatrix} \tag{4}$$

The determinate of the Jacobian is zero along the baseline. A range measurement shortfall along the baseline results in no possible solution. Therefore operation along the baseline

should be avoided.

The precision of X and Y positions is a function of crossing angle of the tangents to the respective range arcs. For a given range variance, the most accurate position occurs when tangents to the range arc cross at 90 degrees. Precision fall off as the angle between the tangents decreases. Changes in X and Y position as a function of angle and change in range:

$$\begin{bmatrix} dX \\ dY \end{bmatrix} = \begin{bmatrix} \cot\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right) & \cot\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right) \\ \cot\left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right) & \cot\left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right) \end{bmatrix} \begin{bmatrix} dR1 \\ dR2 \end{bmatrix} \tag{5}$$

Precision can be expressed as the angle between the received range arc tangents. Figure 2 shows the geometry of the position uncertainties. Figures 3 and 4 show how the coordinate transformation affects the X and Y uncertainty for a set range uncertainty for crossing angles between 0 and 90 degrees. For all cases one coordinate position error is reduced by a factor between 1 and 0.707 while for the other coordinate the error is increased by a factor of 0.0707 to infinity. At 30 degrees crossing angle the magnification factor is 3.5 and reaches the limit of acceptability. This locus of 30 degree crossing normalized for a baseline length of unity is shown in Figure 5. At an angle of 30 degrees the X position deviation is reduced by a factor of 0.95, but the Y position deviation is increased by a factor of 3.5.

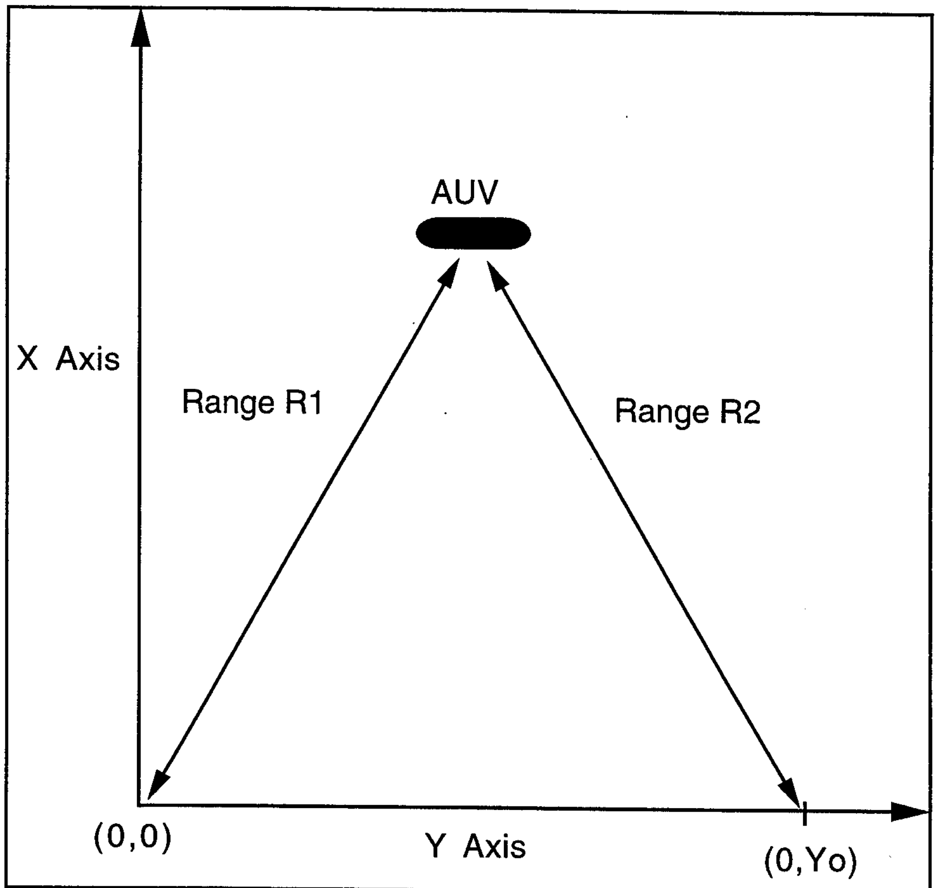

Figure 1 Coordinate System

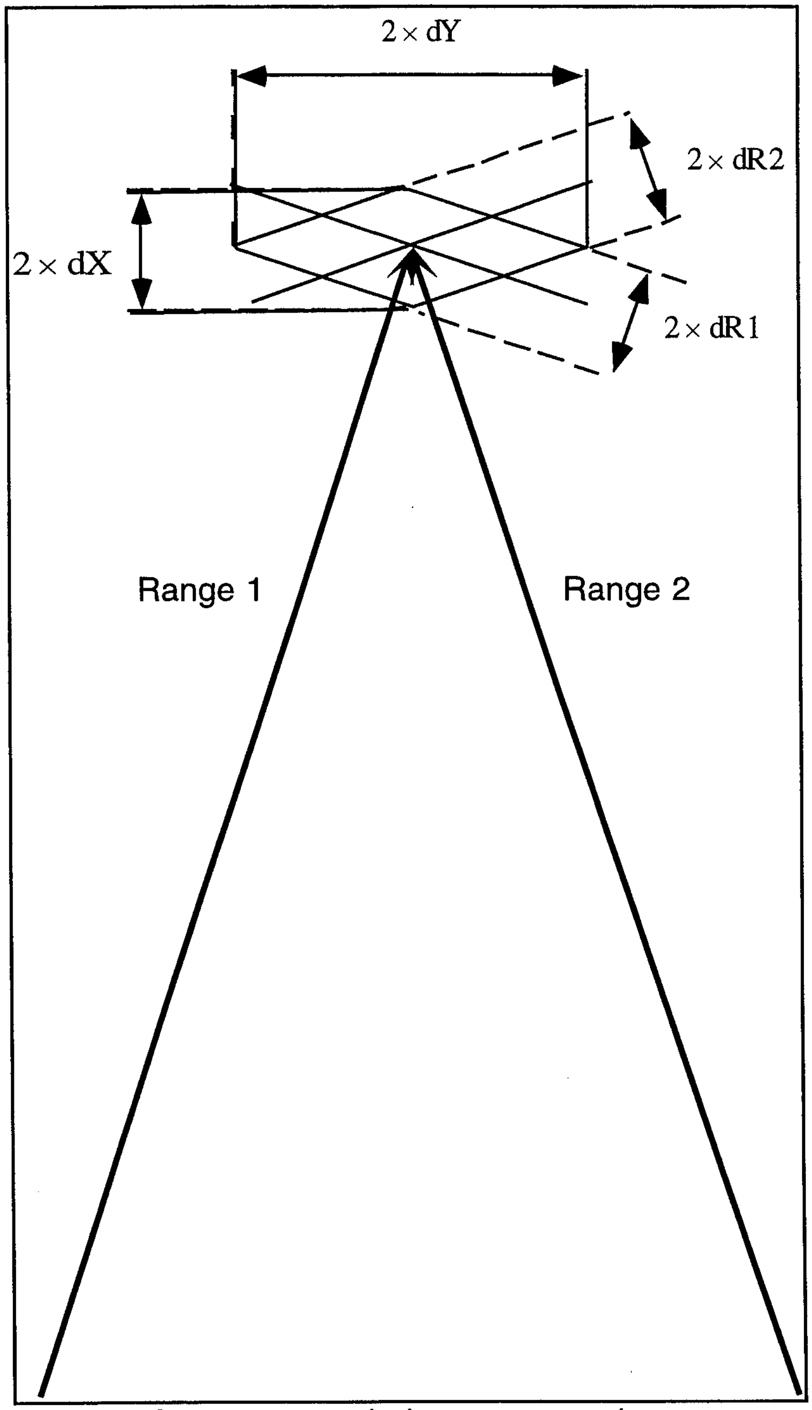

Figure 2 Position Uncertainty

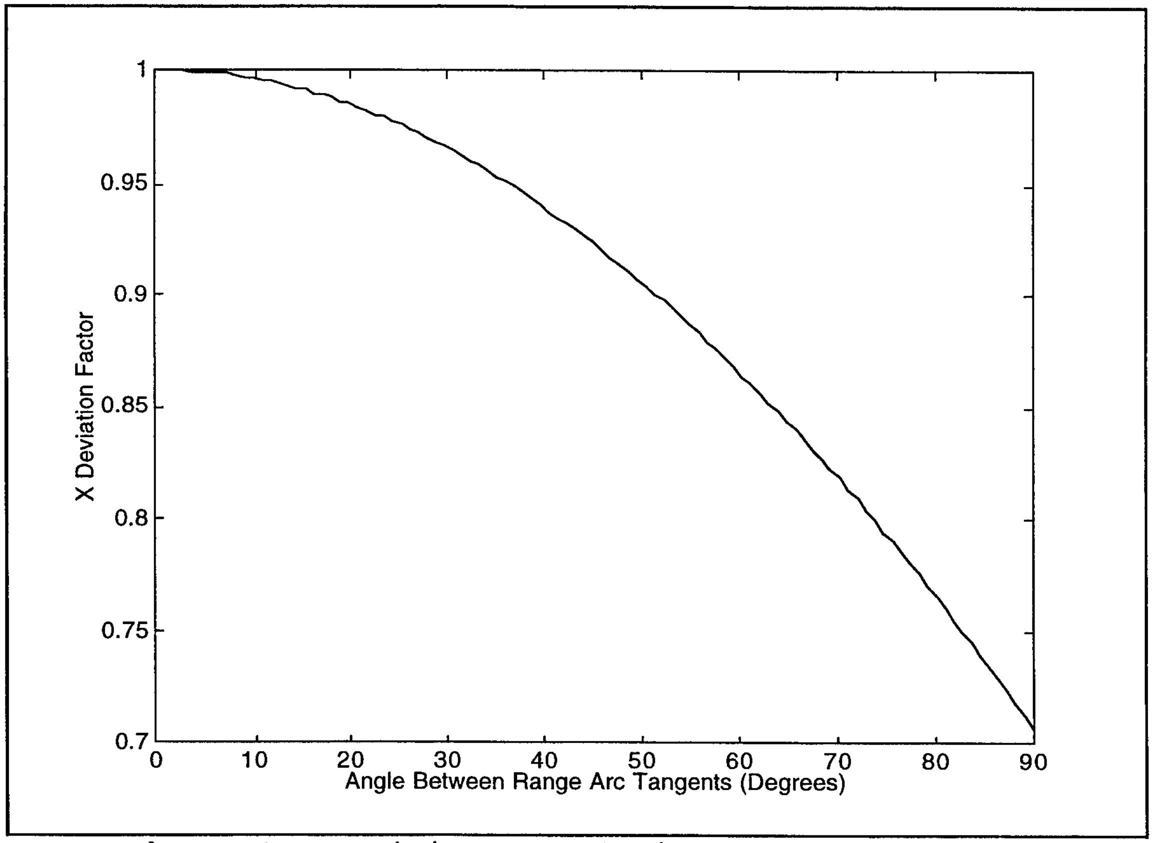

Figure 3 X Position Translation Factor (No Bias)

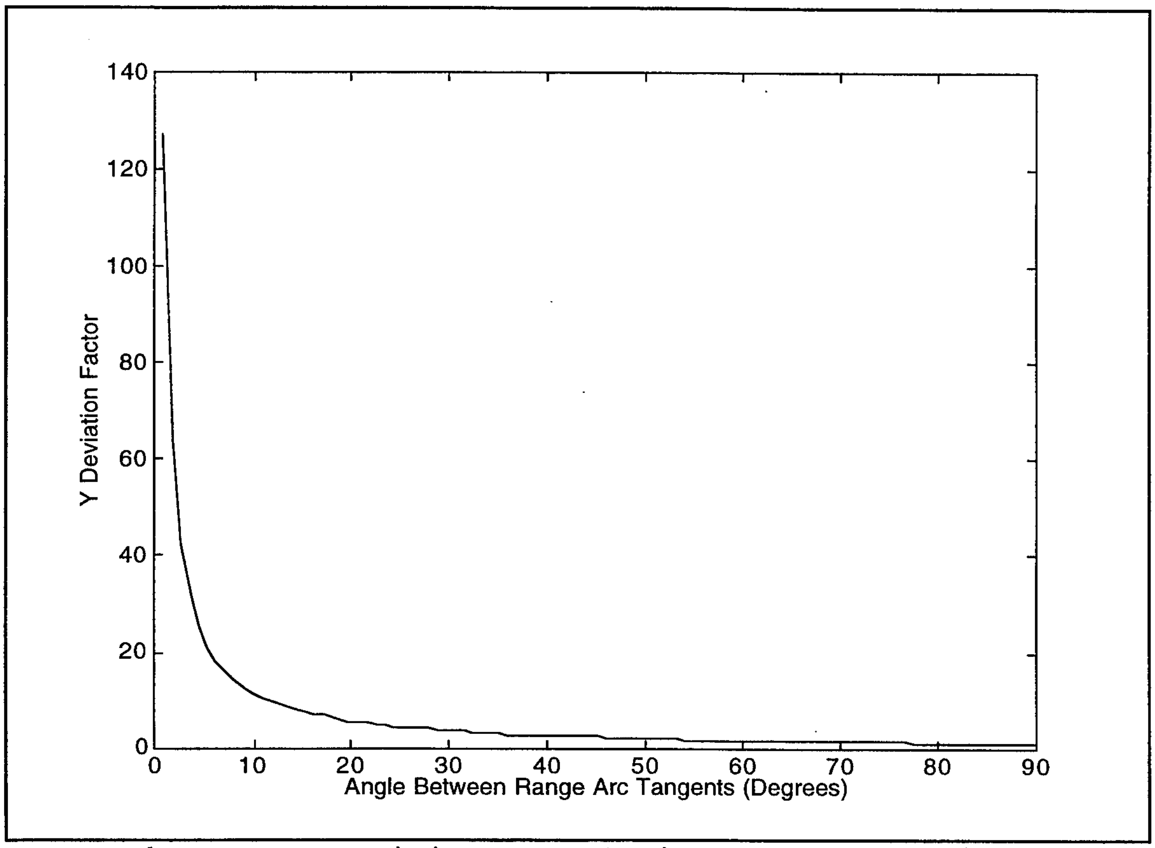

Figure 4 Y Position Translation Factor (no Bias)

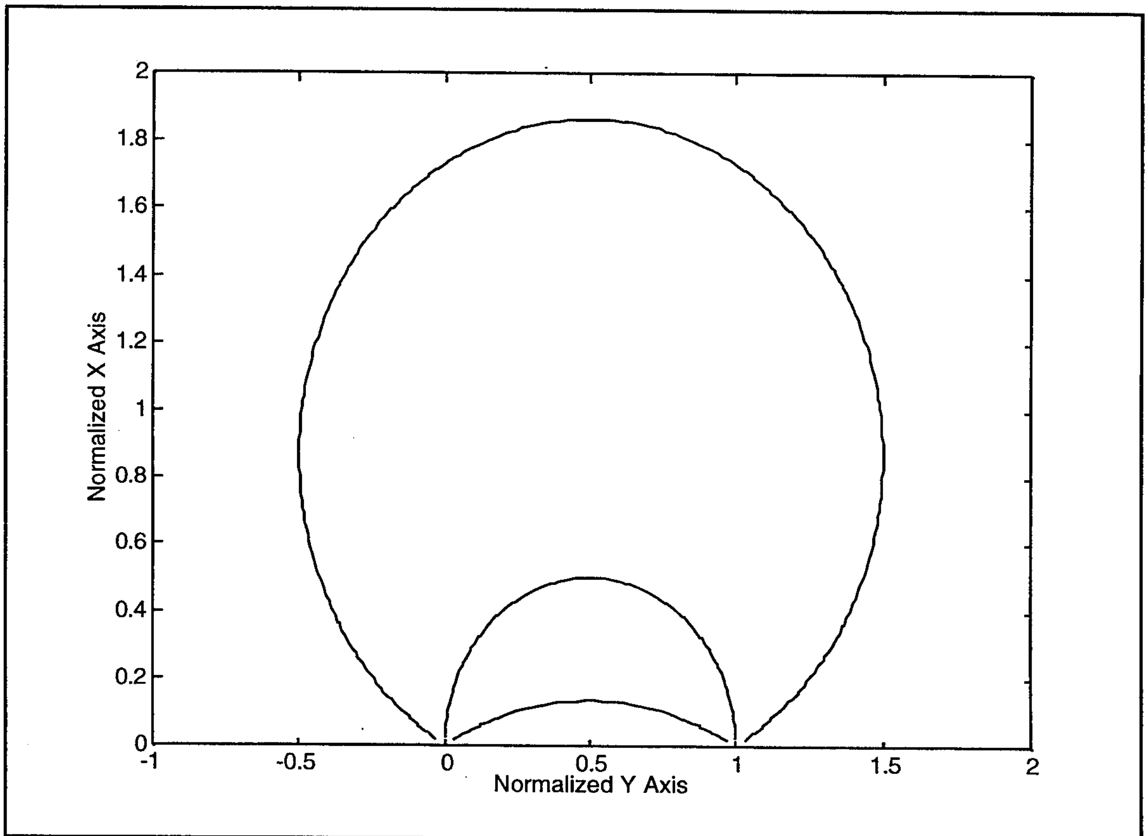

Figure 5 Normalized Operating Area

III. DIVETRACKER SYSTEM

The DiveTracker system is a commercially produced system for underwater navigation, communications, and diving support. It consists of both hardware and software subsystems. It is produced by Desert Star Systems for use by divers and underwater vehicles and represents a low cost, but simple solution for short range shallow water navigation where putting antenna through the surface is not desirable. Major system components are shown in Figure 6.

A. DIVETRACKER HARDWARE

The Divetracker hardware is a consists of sonar transducers, mobile unit, 'surface' station, and connecting cabling. The system in available in various configurations depending upon display and navigation requirements. Divetracker Model DT1-MOD mobile unit, a single DT1-D-TDCR-40 transducer, and connecting cabling are used in the Phoenix AUV to provide navigation information to the AUV. A Divetracker Model DT1-DRY, two DT1-D-TDCR-40 transducers and connecting cabling are used for the surface station. For testing of the system without the Phoenix AUV a Divetracker Model DT1-D-S, a single DT1-D-TDCR-40 transducer, connecting cabling, and a Zenith 248 portable computer are used to simulate the Phoenix AUV. DiveTracker hardware is shown in Figure 6.

1. DiveTracker Model DT1-MOD

The Divetracker Model DT1-MOD used in the Phoenix AUV is an electronics module mounted on an aluminum support structure. The chassis measures 6 inch by 3 inch by 1.75 inches The unit incorporates a MC68HC11 microprocessor

operating at 1MHz, 256 Kbyte of permanent flash memory, 24 Kbyte of EPROM (electronically programmable read only memory) for the SmartDive software, 256 Kbyte of flash memory for DiveCode storage, 256 Kbyte of RAM (read only memory) for data storage. Data input/output is through a RS232 serial data link to the execution level program. Power requirements are 840 mWatts. A five pin connector provides link to the external sonar transducer. The DT1-MOD receives the signal from the transducer, and using the SmartDive software computes the ranges and provides the data to the Gespac computer in the Phoenix AUV. The DT1-MOD also handles the timing sequence for the sonar replies from the Phoenix AUV. [Reference 5 p. 4-22]

2. DiveTracker Model DT1-DRY

Divetracker Model DT1-DRY used for the surface station is identical to DT1-MOD with the electronics enclosed in a splash proof polycarbonate case measuring 6.75 inches by 5.25 inches by 2.2 inches. The unit weighs 22 ounces An external power supply of 9 volts DC at 1 Amp peak is required. Four five pin connectors provide the links the sonar transducers, serial communications to a personal computer, and power input connection. The DT1-DRY provides the same functions for the surface station as the DT1-MOD does for the Phoenix AUV with the difference in that it is connected to two transducers vice as single transducer for the DT1-MOD. [Reference 1 p. 5-18]

3. DiveTracker Model DT1-D-S

Divetracker Model DT1-D-S is enclosed in a water tight hard anodized aluminum chassis measuring 8.5 inches by 3.5 inches by 2.16 inches. The unit has the microprocessor and

memory of the DT1-MOD and incorporates a 64 by 128 pixel liquid crystal display with backlighting and 16 key solid state keyboard. A five pin connector provides the link to the sonar transducer. A second five pin connector provides the serial link to a personal computer and provides for the battery charging connection. The DT1-D-S was used to simulate the Phoenix AUV system. The DT1-D-S connected to a single transducer and laptop computer acted as a mobile station and provided received ranges to the laptop. [Reference 1 p. 2-34]

4. DT1-D-TDCR-40

The DT1-D-TDCR-40 is the external sonar transducer used by the divetracker system. The sonar operates from 33 KHz to 41 KHz. Horizontal beamwidth is 360 degrees. Vertical beamwidth is 88 degrees. Transmit sound pressure level is a maximum of 169 dB reference to 1 microPa at 1 meter. The transducer has an omni-directional pattern in the horizontal plane (perpendicular to cable mounting axis. The transducer can be mounted such that the cable is either pointing up or pointing down. Three transducers were used for the acoustic navigation system. Two transducers connected to the DT1-DRY formed the short baseline, and one transducer connected to either the DT1-MOD in the Phoenix AUV or the DT1-D-S acted as the mobile station. [Reference 1 pp. 1-11 through 1-13]

B. DIVETRACKER SOFTWARE

The Divetracker system uses three C language based programs (SmartDive, DiveBase, and DiveTerm) to implement the navigation and communication features of the system. SmartDive is the application software used by each DiveTracker for the navigation and communication functions.

DTOS is the operating system used by the DiveTracker stations. SmartDive program runs under the DTOS operating system on the DiveTracker stations. SmartDive versions 1.2.1 and 1.2.3 were used during testing. DiveBase is an MS-DOS program for the surface station personal computer and the mobile unit. DiveTerm is a MS-DOS based utility program to download application software to the DiveTracker stations. Under the DiveBase software, several programmable features are controlled using the DiveBase parameters file. [Reference 1 p.1-2]

1. DIVEBASE PARAMETER FILE

The DiveBase parameter file, divebase.par, controls the mission specific setting of the DiveTracker system. The sonar navigation protocols, sonar and communications parameters are configured under the divebase.par file. This configuration file is shown in Appendix A. Parameters of interest to this study were transmit power level, receive gain sensitivity receive threshold level, rest time between pulses, and baseline length.

2. DiveTracker Navigation Protocol

The DiveTracker system uses a continual pinging system to determine range from the baseline transducers. Range is calculated from the time difference between sent and received sonar pulses or pings in a way that both the mobile unit and the surface station retain information concerning the position of the mobile unit. The transducer pinging schedule is show in Table 1.

Time Index	Action	Result
1	Surface Station transducer 1 pings.	
2	Mobile unit receives ping and replies.	
3	Surface Station transducer 1 receives ping and replies.	Surface Station calculates range from Mobile Unit to transducer 1 based on time 3-1.
4	Mobile Unit receives ping and replies.	Mobile Unit calculates range from Diver to transducer 1 based on time 4-2. (Time index 1 through 4 constitute one pinging cycle.)
5	Surface Station transducer 2 receives ping and Surface Station transducer 1 replies	Surface Station calculates range from Diver to transducer 2 based on time 5-3.
6	Mobile Unit receives ping and replies.	Mobile Unit calculates range from Diver to transducer 2 based on time 6-4.

Table 1 DiveTracker Pinging Protocol

DiveTracker DT1-MOD range calculations:

$$\text{Range 1} = \frac{\text{Time 4} - \text{Time 2}}{\text{Speed of Sound}} \tag{6}$$

$$\text{Range 2} = \frac{\text{Time 6} - \text{Time 4}}{\text{Speed of Sound}} - \text{Range 1} - \text{Baseline Length} \tag{7}$$

Figure 7 shows the layout of the system in use.

C. DIVETRACKER IMPLEMETATION

For experiments in the MBARI Moss Landing Basin the following parameters were used:

Baseline length	various - 6.1 to 14.6 meters (20 to 48 feet)
Transmit power	Maximum of 60 Watts
Pulse length	4000 microseconds
Detection threshold	12
Transducer turnaround	0.1 seconds
Maximum range	1828 meters (6000 feet)

The complete configuration file is shown in Appendix A.

D. DIVETRACKER LIMITATIONS

DiveTracker SmartDive software assumes a speed of sound in water of 1494 meters per second corresponding to a sea water temperature of 11°C. Operations in sea water of significantly different temperature will introduce a bias error in the ranges provided by DiveTracker. The Divetracker system is suitable for underwater navigation of AUV's in open ocean scenarios. The system has an advertised range of 600 meters (2000 feet) based on transmit power at 40 kHz. Testing in the Moss Landing Basin demonstrated a range limit of approximately 150 meters. This reduced performance may be caused by the shallow soundings (less than 20 feet)and the soft mud bottom conditions of the Moss Landing channel. As implemented both shore transducers must be connected to the surface station by cables, limiting the maximum baseline length. As the size of the area of most accurate navigation is a function of baseline length, this restriction on baseline length limits the area of employment of DiveTracker.

Under current ranging protocol the R2 range calculation adds any R1 range error and baseline error to the R2 range error. The R2 range will have a greater uncertainty than the R1 range.

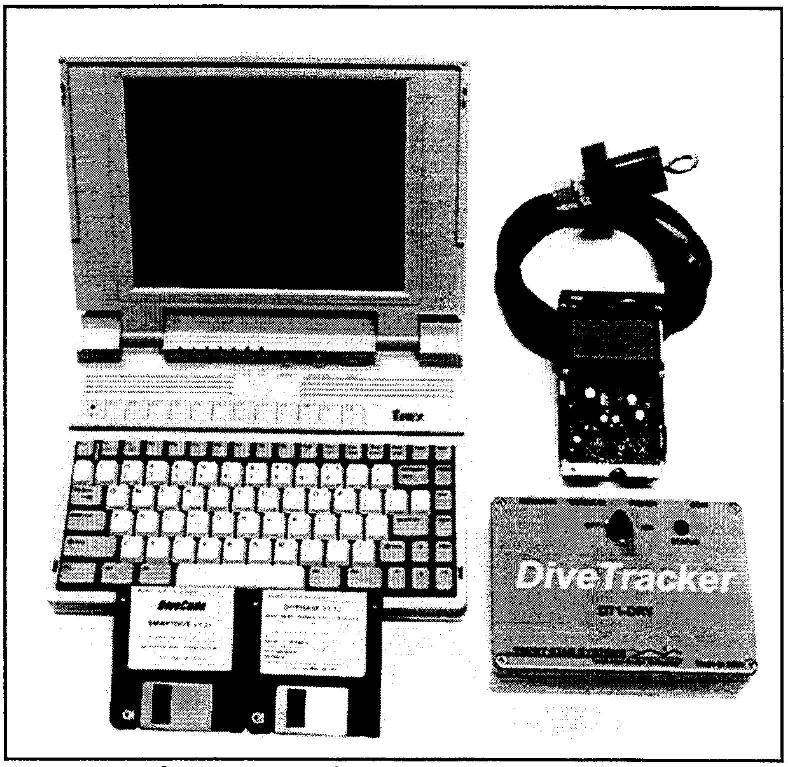

Figure 6 DiveTracker System
PC, Software Disks, DT1-Mod, DT1-Dry,
40KHz Transducer

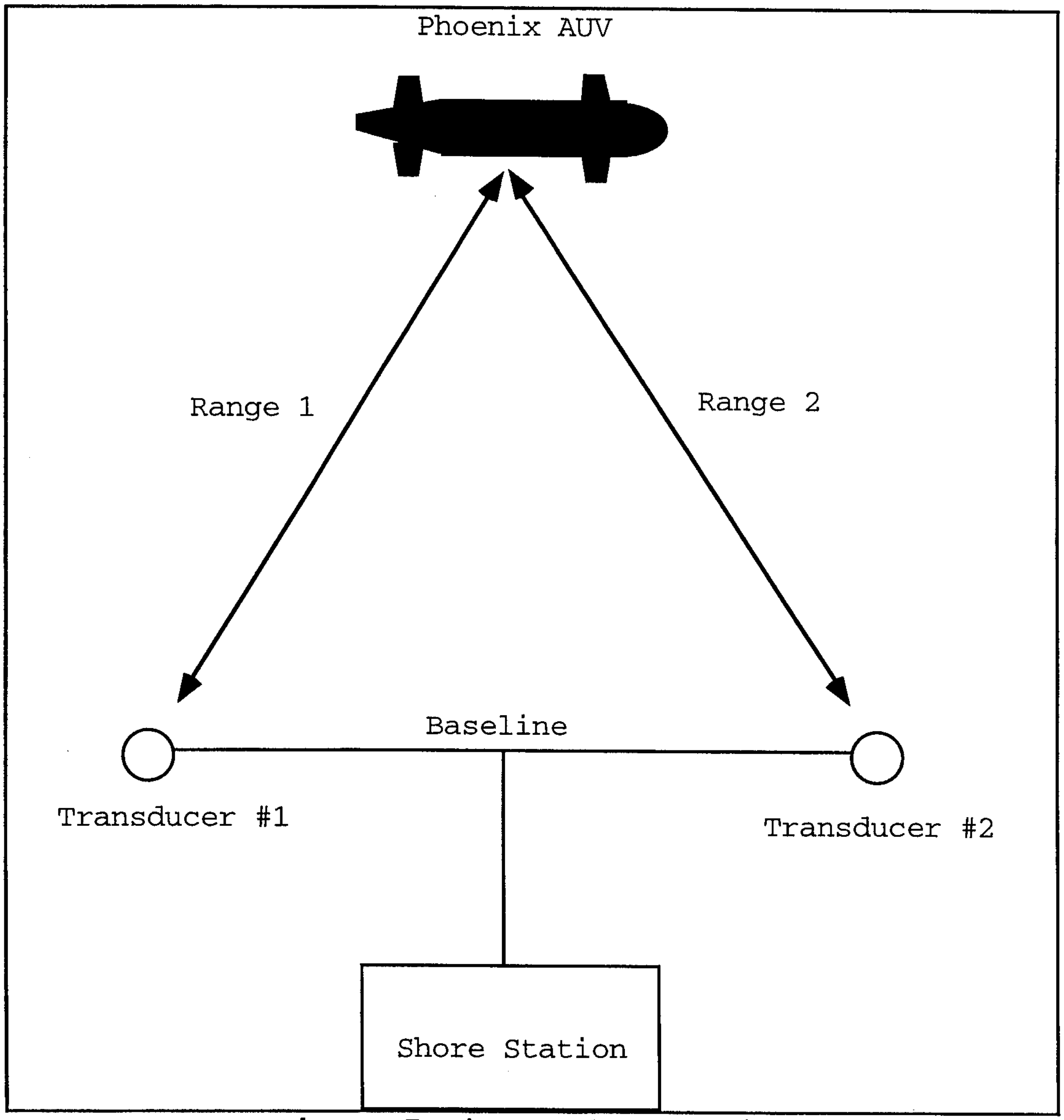

Figure 7 DiveTracker Ranging

IV. PHOENIX AUTONOMOUS UNDERWATER VEHICLE

A. PHYSICAL DESCRIPTION

The Phoenix Vehicle, shown in Figures 8 and 9, is an autonomous underwater vehicle designed for research in intelligent control. The vehicle incorporates TRITECH ST1000 and ST725 high frequency sonars to provide data about the environment. Motion behavior at slow speed is controlled by the four cross body thrusters and two propulsion thrusters. When moving at speed, eight control fins and the two propulsion thrusters provide control. The control system is implemented in hardware using two networked processors. All execution level software operates under the OS-9 operating system on a GESPAC M68030 processor in a separate card cage in the vehicle. Connected in the same card cage is an ethernet card and array of real time interfacing devices for communications to sensors and actuators. A Sun Voyager computer is located in the Phoenix run the tactical level software written in "C" code and the strategic level software written in Prolog. The Divetracker Model DT1-MOD output is connected to the Gespac processor via a serial connection.

B. SOFTWARE DESCRIPTION

The Phoenix AUV control software operates on three levels. Strategic level software uses Prolog rules to specify the mission to be conducted. The Tactical level software links with the Strategic software and sends the vehicle the primitive commands necessary for vehicle operation. At the Tactical level separate processes operate in the Sun Voyager computer simultaneously under the paradigm of a U. S. Navy submarine command structure with an Officer of the Deck process, Navigator process, Sonar process, and

Engineer process. The Execution level software is composed of the software drivers necessary for the vehicle hardware operation. Execution level software reads the DiveTracker Model DT1-MOD output and passes the data up to the Tactical level for evaluation. The Execution level software performs all necessary control functions such as autoheading, autodepth, autospeed, and hover commands as requested by Tactical level code blocks.

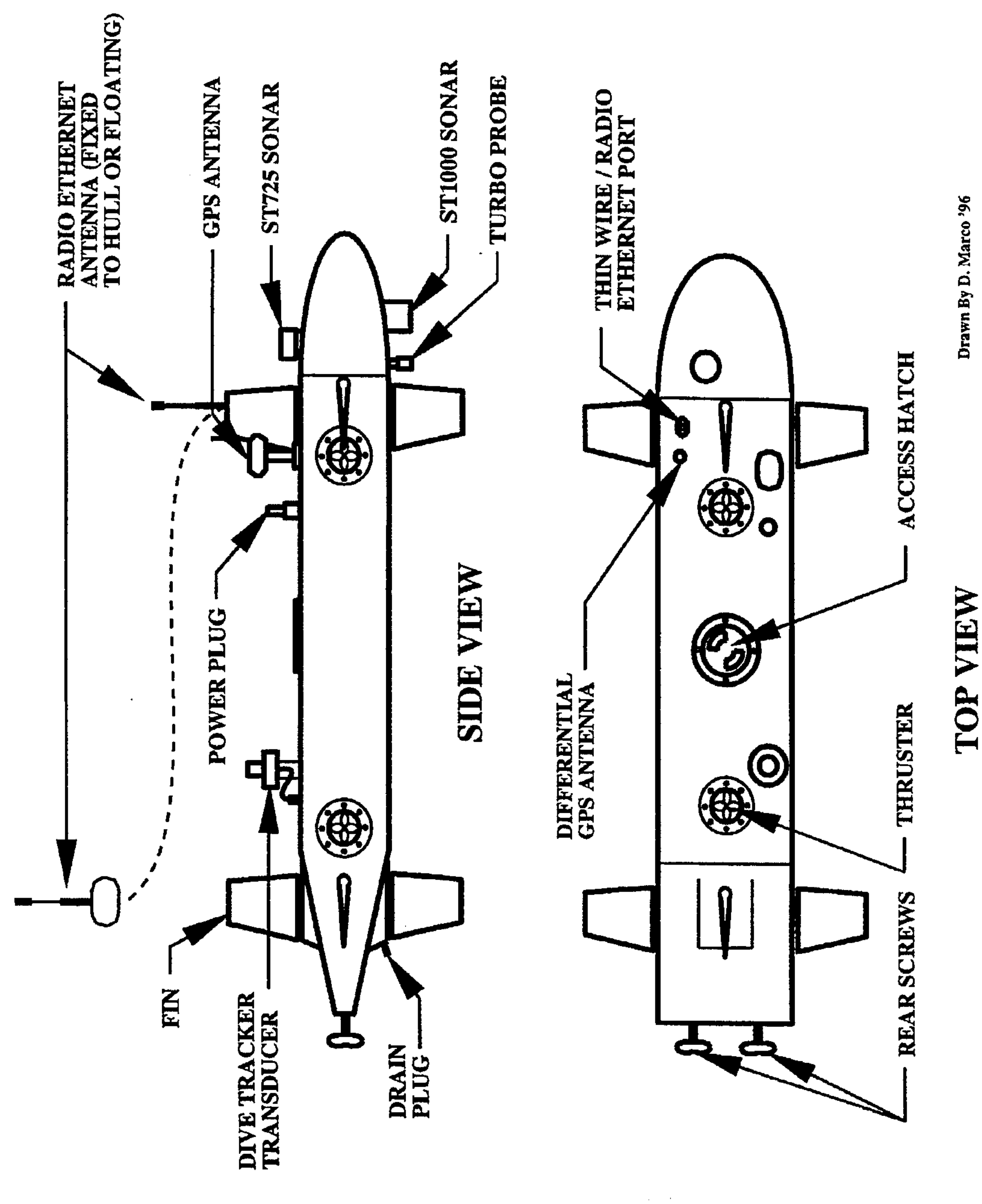

Figure 8 Phoenix AUV External View

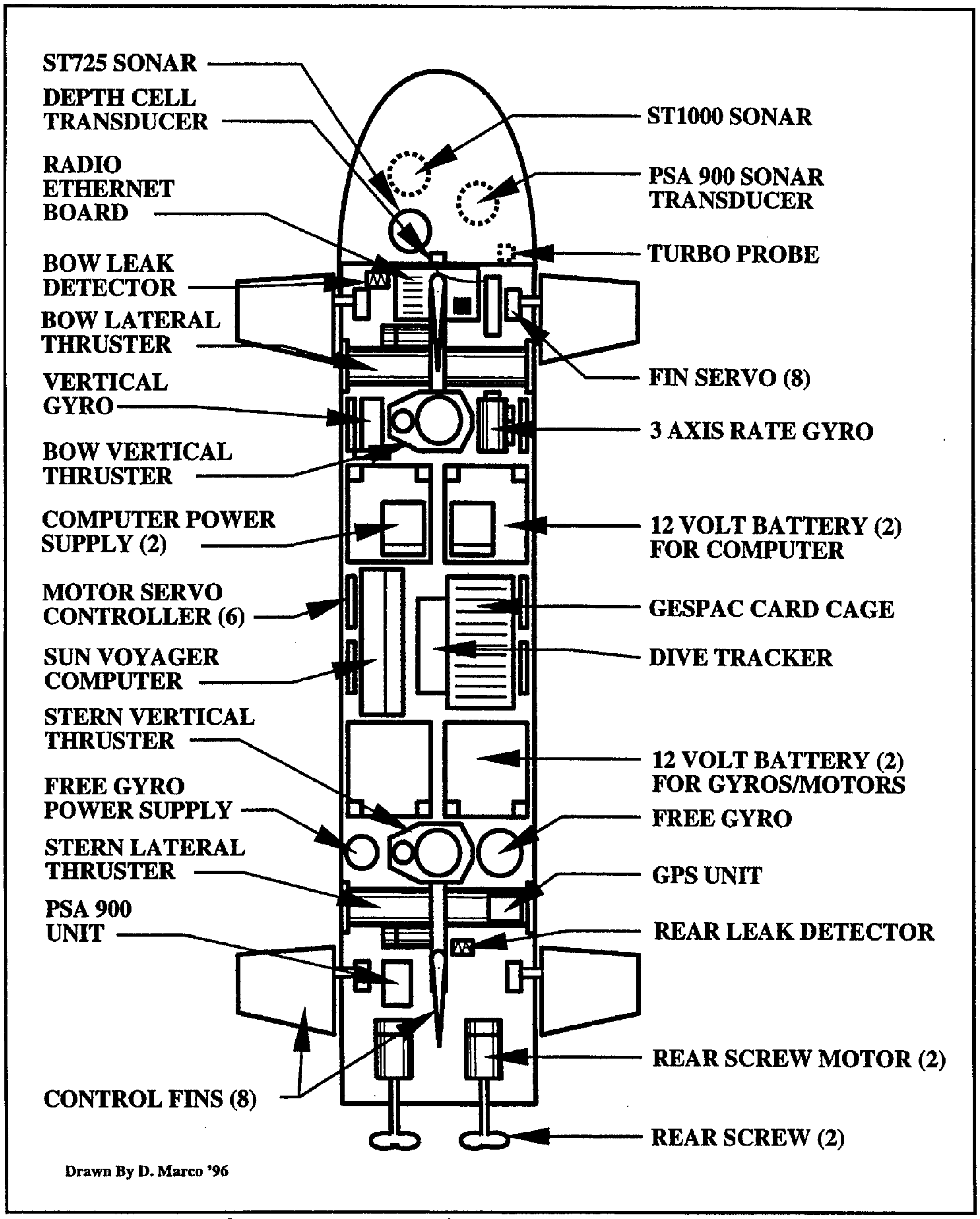

Figure 9 Phoenix AUV Internal View

V. EXPERIMENTAL PROCEDURE

DiveTracker range data were obtained using both the stand alone Divetracker Model DT1-D-S Mobile Unit and Phoenix AUV in conjunction with the Divetracker Model DT1-DRY surface station. Data runs were obtained in the Monterey Bay Aquarium Research Institute (MBARI) boat basin at Moss Landing, California. Testing without the Phoenix AUV was conducted to validate the DiveTracker system and determine the optimal software and hardware configurations for later testing with the Phoenix AUV. Testing with the Phoenix AUV was conducted to validate vehicle control and use of the position data during an autonomous mission using the DiveTracker system as the primary navigation system.

A. TESTING WITHOUT PHOENIX AUV

Testing was conducted at the MBARI basin using the DiveTracker DT1-DRY surface station and Divetracker Model DT1-D-S Mobile Unit. The surface station consisted of the DiveTracker DT1-DRY connected to a Zenith desktop personal computer and two DT1-D-TDCR-40 transducer baseline which was placed at various locations around the basin. The mobile unit consisted of the Divetracker Model DT1-D-S connected to a Zenith 286 laptop computer and single DT1-D-TDCR-40 transducer to simulated the Phoenix AUV. Ranges were recorded with the mobile unit and transducer stationary and moving in a small rowboat. Raw ranges were recorded on floppy disk by a Zenith 286 laptop computer. No time data for the raw ranges were available for this testing configuration. Divebase configuration file parameters such as transmit power level and receive sensitivity threshold were varied to determine optimal setting for future operations in the MBARI basin with the Phoenix AUV.

B. TESTING WITH THE PHOENIX AUV

In water testing with the Phoenix AUV was conducted from January 26 to February 2, 1996 at the MBARI basin. The same surface station as used in the simulated testing was used. Nineteen separate runs were conducted using various planned missions. For all runs except 2-02-1, the surface station baseline arrangement of along the southern edge of the basin was used as shown in Figure 10. For run 2-02-1, the baseline was placed along the pier at the north end of the west side of the basin. Inside the AUV, DiveTracker model DT1-MOD outputed range data to the Gespac computer. Range data was passed to and stored by the Voyager computer as part of the AUV state vector telemetry on the Phoenix AUV and downloaded post mission via the "thin wire" Ethernet connection.

Testing runs are identified using the convention of Month-Day-Daily Run Number. For all runs the Phoenix AUV was manually placed at the starting point. The Phoenix AUV was submerged sufficiently to wet the DiveTracker transducer and establish track with the surface station. In order to initialize the Phoenix AUV for each mission the vehicle was broached out of the water in order to receive GPS and DGPS signals via antennae mounted on top of the Phoenix AUV. This brought the DiveTracker transducer out of the water, and interrupted the pinging sequence on the DiveTracker system. During testing on January 29 and January 30, this initial broach of the vehicle caused the surface station to go into a sleep mode. Once the vehicle submerged to under 2 feet, DiveTracker pinging sequence was not re-established in sufficient time to prevent mission abort on loss of DiveTracker signal. This problem was overcome by increasing the loss of DiveTracker abort from 10 seconds to 45 seconds and by upgrading the SmartDive program to version 1.2.3. For

missions on January 31 and February 1, no DiveTracker related mission aborts occurred. For the single mission attempt on February 2, the Phoenix AUV was started adjacent to the baseline. The Phoenix AUV navigator program incorrectly solved for the X axis solution on the opposite side of the baseline than the vehicle actually was.

Description of significant test runs:

Run 1-31-3

This mission was started 16m north of transducer 1 on a heading of north. The mission was designed to test the Phoenix ability to hover at a designated point. The vehicle operated for approximately 500 seconds.

Run 2-01-2

This mission was started 16m north of transducer 1 on a heading of north. This mission was designed to test calibration of the forward motion speed model. The vehicle initialized at the starting location, transitted at maximum speed to a point 28m north of transducer 1 and hovered for approximately 200 seconds.

Run 2-01-7

This mission was started 16m north of transducer 1 on a heading toward transducer 1. This mission was designed to be a complete test of the Phoenix AUV. Unfortunately 107 seconds into the mission the Voyager computer battery voltage dropped low causing the strategic and tactical programs to fail.

Run 02-01-2

This mission was started 1m north of the baseline midpoint. The mission was designed to transit north and search for the mine-like object. However the Navigator software module incorrectly calculated that the Phoenix AUV was on the south side of the baseline. Although the DiveTracker correctly tracked the vehicle, the incorrect

Navigator solution generated false control signals. The mission was aborted after approximately 10m travel.

Following completion of testing, all telemetry data was transferred to the Naval Postgraduate School Mechanical Engineering computer laboratory for analysis.

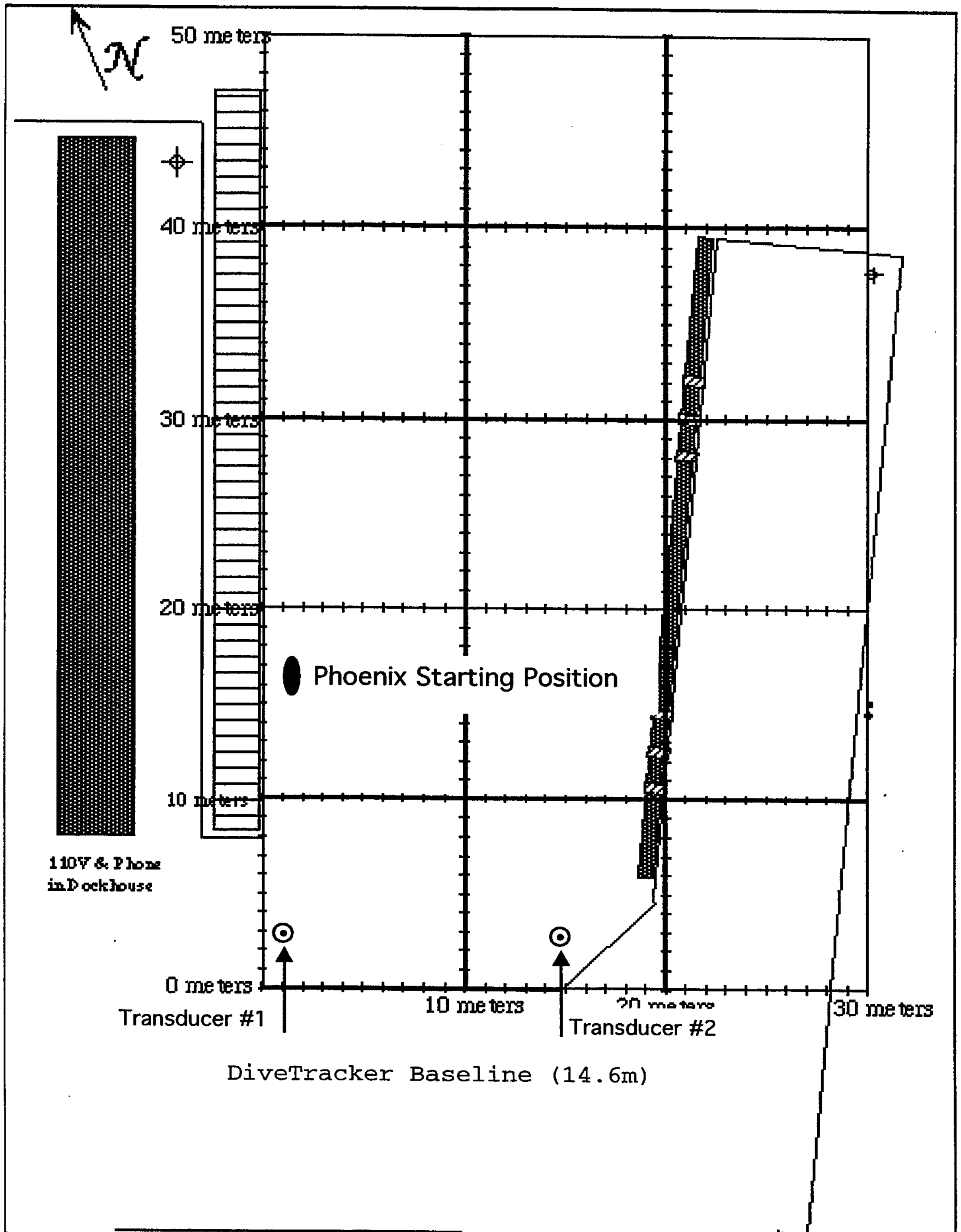

Figure 10 Moss Landing Test Setup

VI. RESULTS

The mission runs were analyzed to determine the viability of DiveTracker in providing precise navigation data and to determine the best method of filtering the data to improve the precision. Without a secondary position reference providing information of greater precision than DiveTracker, no absolute reference position was available for the Moss Landing data. Therefore analysis relies on comparing the filtered data to raw data, and accessing the variability seen in the raw signals. The first step in data analysis was separating out those state vector values for which a DiveTracker range was received using Matlab. Then using Matlab, two methods of filtering the navigation data were analyzed. First, the ranges were smoothed using a Kalman filter and translated into X and Y coordinates for analysis and plotting. Alternatively, the ranges were first translated into X and Y and then smoothed using the Kalman filter then analyzed and plotted.

A. KALMAN FILTER

If a process is affected by random white noise in both the system and the output measurement, then Kalman filtering techniques offer a method of reducing the output fluctuations. The Kalman filter used was based on the discrete time filter used by the Phoenix AUV sonar process. The filter uses a three state model of position, velocity and time. Output of the model is position. System noise is assumed to variation in the acceleration of the model. Measurement noise is added onto the output of the process. The Kalman filter is a recursive method in that it improves the estimate of a state value based on the previous value. Assumptions of the Kalman filter are the both the system

noise and measurement noise are random with a mean value of zero and that the noise is constant for each time step. For each update cycle the measured state is compared with prior estimates and are weighted by Kalman gains to obtain updated state estimates for position, velocity and acceleration.

The continuous system model is:

$$\begin{aligned} \dot{x} &= Ax + Bw_1 \\ y &= Cx + w_2 \end{aligned} \tag{8}$$

where

x = state vector of positon, velocity, acceleration

$\dot{x}$ = time derivative of state vector

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, C = [1 \ 0 \ 0]$$

w_1 = system noise

w_2 = measurement noise

The discrete time system model is:

$$\begin{aligned} x_{k+1} &= \Phi x_k + \Gamma w_{1k} \\ y_k &= Cx_k + w_{2k} \end{aligned} \tag{9}$$

where

$\Phi = e^{Adt}$

$\Gamma = \left(I - e^{Adt}\right) A^{-1} B$

dt = time step

The formula for the Kalman filter is derived by optimizing the assumed form of the linear estimator. The state estimate at time k+1 based on time k data is:

$$\hat{x}_{k+1/k} = \Phi\hat{x}_{k/k} + \Gamma w_1 \tag{10}$$

The use of the subscript k+1/k defines a value at the k+1 time step based on the k (previous) time step. The k+1/k+1 defines a value at the k+1 time step based on updated information at the k+1 time step. The covariance of the estimate of the state is given by:

$$P = E\left\{\tilde{x}_{k+1/k+1}\tilde{x}^T_{k+1/k+1}\right\} \tag{11}$$

In matrix form:

$$P = \begin{bmatrix} \sigma^2_{xx} & \sigma^2_{xv} & \sigma^2_{xa} \\ \sigma^2_{vx} & \sigma^2_{vv} & \sigma^2_{va} \\ \sigma^2_{ax} & \sigma^2_{av} & \sigma^2_{aa} \end{bmatrix} \tag{12}$$

where

$\sigma_x =$ Standard deviation of positon

$\sigma_v =$ Standard deviation of velocity

$\sigma_a =$ Standard deviation of acceleraton

The error covariance before update is calculated by:

$$P_{k+1/k} = \Phi P'_{k/k}\Phi^T + \Gamma Q \tag{13}$$

The optimal gain is calculated by:

$$G_{k+1} = \frac{P_{k+1/k}C^T}{CP_{k+1/k}C^T + R} \tag{14}$$

where

$$Q = w_1^2 \text{ System noise}$$

$$R = w_2^2 \text{ Measurement noise}$$

The updated covariance matrix is:

$$P_{k+1/k+1} = \left[I - G_{k+1}C\right]P_{k+1/k} \tag{15}$$

The updated state estimation is:

$$\hat{x}_{k+1} = \Phi\hat{x}_k + G_k\left[y_k - C\hat{x}_k\right] \tag{16}$$

The term $\left[y_{k+1} - C\hat{x}_k\right]$ represents the 'innovation' for each time step, [Reference 6]. While most Kalman filters operate at a fixed update rate, the DiveTracker system operates asynchronously based on time of reception of the sonar pings. This variable time step requires recalculation of the conversion of state space models from continuous to discrete time at every cycle. Equations (13) through (16) are used in the Kalman filter program given in Appendix B.

B. NOISE CHARACTERISTIC

Kalman filtering assumes that the noise is random and follows a Gaussian distribution. For the most significant mission runs, the filtered data was compared to the raw data. Figures 11 through 19 show the histograms of difference between estimated and measured data which represents the innovation with Gaussian overlay. While the differences are not perfectly Gaussian, the general trend follows the Gaussian distribution and allows for use of Kalman filtering in noise reduction. Due to the sonar pinging protocol used by the DiveTracker system error in the R1 range measurement are added to the R2 range measurement errors. As shown in Table 2, the R2 range has approximately twice the standard deviations of R1 range.

C. FILTER TUNING

In order to tune the filter to smooth out data values for sensory noise and process noise were varied. Three values of system noise to measurement noise ratio analyzed for the filter were 1:1000, 1:100,000, and 1:10,000,000. For the analysis method of filtering ranges then translating into position the standard deviation values for R1 and R2 ranges are given in Table 2. For the method of translating then filtering, the standard deviation values for X and Y positions are given in Table 3. Without a reference position for each run the deviations are between the estimated and measured data. The objective was to smooth out the Phoenix track without excessively lagging behind the position. Therefore it was judged that the medium speed filter performed the best. The filtered and raw range and position plots are shown in Figures 20 through 28.

Run	Filter Speed	R value	Q value	Sigma R1 (m)	Sigma R2 (m)
1-29-1	Fast	1e3	1	0.0492	0.2529
	Medium	1e5	1	0.1193	0.4104
	Slow	1e7	1	0.1599	0.5320
1-31-1	Fast	1e3	1	0.1228	0.3154
	Medium	1e5	1	0.2208	0.4487
	Slow	1e7	1	0.5512	0.7918
2-01-2	Fast	1e3	1	0.0707	0.1284
	Medium	1e5	1	0.1604	0.2521
	Slow	1e7	1	0.2423	0.3423
2-01-7	Fast	1e3	1	0.0784	0.1965
	Medium	1e5	1	0.2610	0.7070
	Slow	1e7	1	0.3028	1.3328
2-02-1	Fast	1e3	1	0.1568	0.1699
	Medium	1e5	1	0.2395	0.2763
	Slow	1e7	1	0.7248	1.2067

Table 2 Prefiltering Range Deviations

Run	Filter Speed	R value	Q value	Sigma X(m)	Sigma Y(m)
1-31-3	Fast	1e3	1	0.0506	0.1998
	Medium	1e5	1	0.0506	0.1998
	Slow	1e7	1	0.0506	0.1998
2-01-2	Fast	1e3	1e3	0.0112	0.1074
	Medium	1e5	1	0.0147	0.3690
	Slow	1e7	1e-5	0.1874	0.7761
2-01-6	Fast	1	1	0.0427	0.2134
	Medium	1e5	1	0.0427	0.2134
	Slow	1e7	1e-3	0.1982	0.5187
2-01-7	Fast	1	1	0.0406	02489
	Medium	1e5	1	0.0406	0.2489
	Slow	1e7	1e-3	0.1556	0.5443
2-02-1	Fast	1	1	0.1539	0.3123
	Medium	1e5	1	0.1539	0.3123
	Slow	1e7	1	0.3225	0.5658

Table 3 Postfiltering Position Deviations

D. FILTER INITIALIZATION

Having the DiveTracker transducer mounted on the upper surface on the Phoenix vehicle prevented reception of range information while the vehicle was initializing at the surface and resulted in filter transients greater than expected. Run 2-01-6 (Figure 22) and Run 2-02-1 (Figure 24) show large filter transients than the other runs. This is due to the

vehicle stating motion before the optimal gains have be calculated and the filter has locked on.

For Run 2-01-2 the Phoenix vehicle hovered at the initial submergence point and the filter transients have time to subside prior to vehicle motion. In both prefiltering, (Figure 21), and postfiltering, (Figure 25), analysis ranges and position do not show large transients from the unfiltered data.

E. VALIDATION OF OPERATING AREA

Figure 29 shows the positions for the runs analyzed with loci of 30 degree crossing tangents. Operation at a distance greater than 1.4 times the baseline shows larger variation in the Y position as predicted.

F. COMPARISON OF PREFILTERING AND POSTFILTERING

Comparing the prefiltered positions and postfiltered positions for each run shows that postfiltering yields a reduction in radial deviation in four of five analyzed runs. This demonstrates that the amplification of positional error caused by translating to X-Y coordinates is more than offset through the reduction provided by post-processing through the Kalman filter. When range data is filtered first any remaining deviations are amplified. Figures 30 through 34 compare the prefiltered and postfiltered difference plots. Prefiltering and postfiltering standard deviations as shown in Table 4. Direct comparison of the radial error for each filtering method is not appropriate in that it does not account for the amplification of error as a function of the angle between the range arc tangents. However, even without this magnification factor the postfilering analysis shows a reduced standard deviation compared to the prefiltered

analysis.

Run Number	Prefiltered Ranges	Radial Standard Deviation	Postfiltered Ranges	Radial Standard Deviations
1-31-3	σ_{r1}= 0.1301 σ_{r2}= 0.2541	σ= 0.2855	σ_x= 0.0487 σ_y= 0.1912	σ= 0.1973
2-01-2	σ_{r1}= 0.1604 σ_{r2}= 0.2521	σ= 0.2958	σ_x= 0.0401 σ_y= 0.3597	σ= 0.3619
2-01-6	σ_{r1}= 0.2284 σ_{r2}= 0.2544	σ= 0.3419	σ_x= 0.0383 σ_y= 0.1873	σ= 0.1912
2-01-7	σ_{r1}= 0.2610 σ_{r2}= 0.7070	σ= 0.7536	σ_x= 0.0404 σ_y= 0.2340	σ= 0.2375
2-02-1	σ_{r1}= 0.2395 σ_{r2}= 0.2763	σ= 0.3657	σ_x= 0.1473 σ_y= 0.2962	σ= 0.3308
Average Deviation		σ= 0.4085		σ= 0.2637

Table 4 Comparison of Prefiltering and Postfiltering Deviations

H. FILTER VELOCITY OUTPUT

The Phoenix AUV is equipped with a longitudinal speed sensor termed the "speed wheel". For longitudinal speeds greater than 0.1 meter per second, this sensor provides input to the vehicles dead reconing process. The DiveTracker filter output provides a method of calibrating the gains on the speed wheel in order to improve the dead reconing estimate. For runs headed directly at or away from station 1 transducer, the X velocity was compared to the Phoenix AUV speed wheel output. Figures 36 and 37 show Run 2-01-7 and Run 2-01-7 where the vehicle operated at speed greater than

0.1 meters/second. The Kalman filter X velocity correlates well with the speed wheel data. One of the benefits obtained through the use of the Kalman filter is the estimation of velocity as well as position.

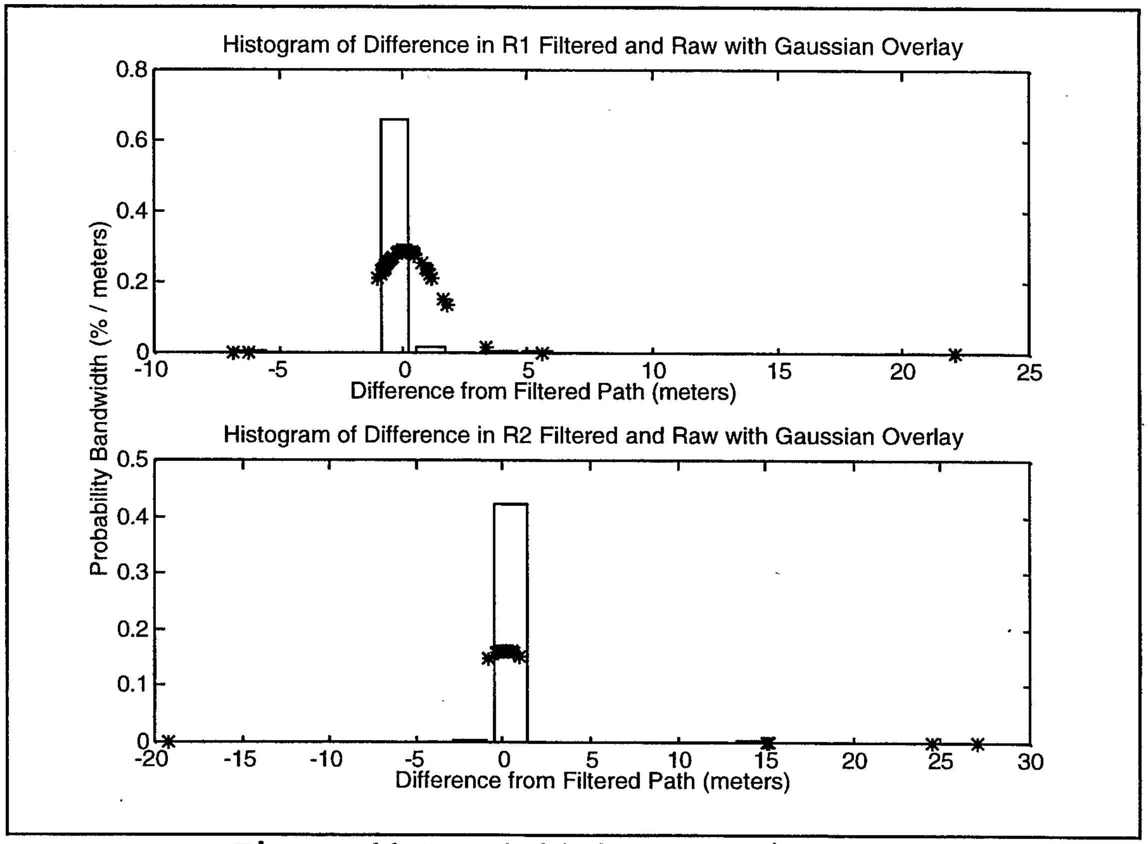

Figure 11 Run 1-31-3 Range Histogram

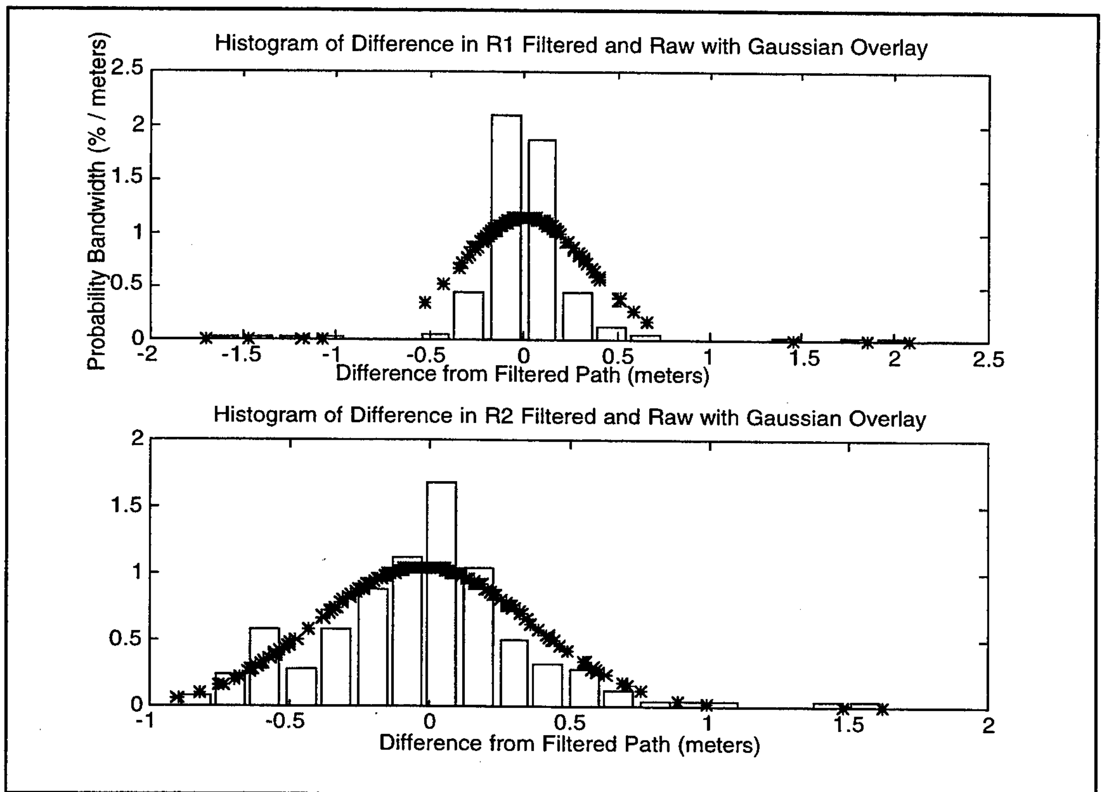

Figure 12 Run 2-01-2 Range Histograms

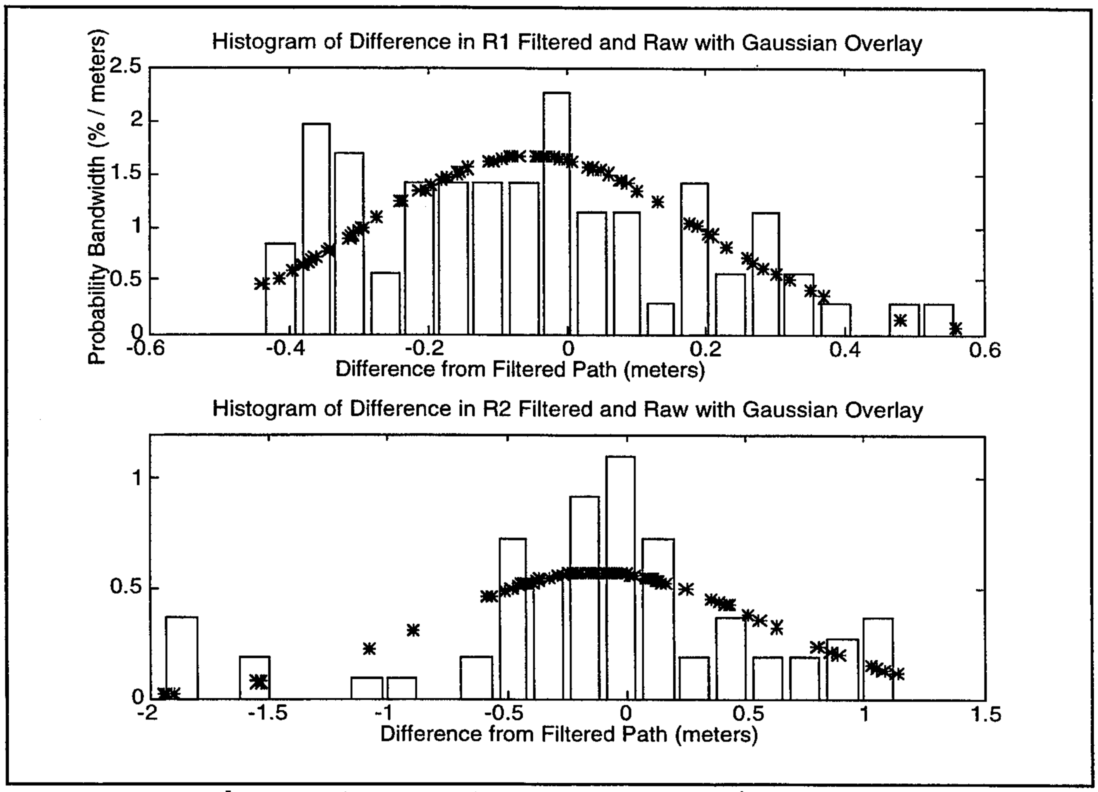

Figure 13 Run 2-01-6 Range Histograms

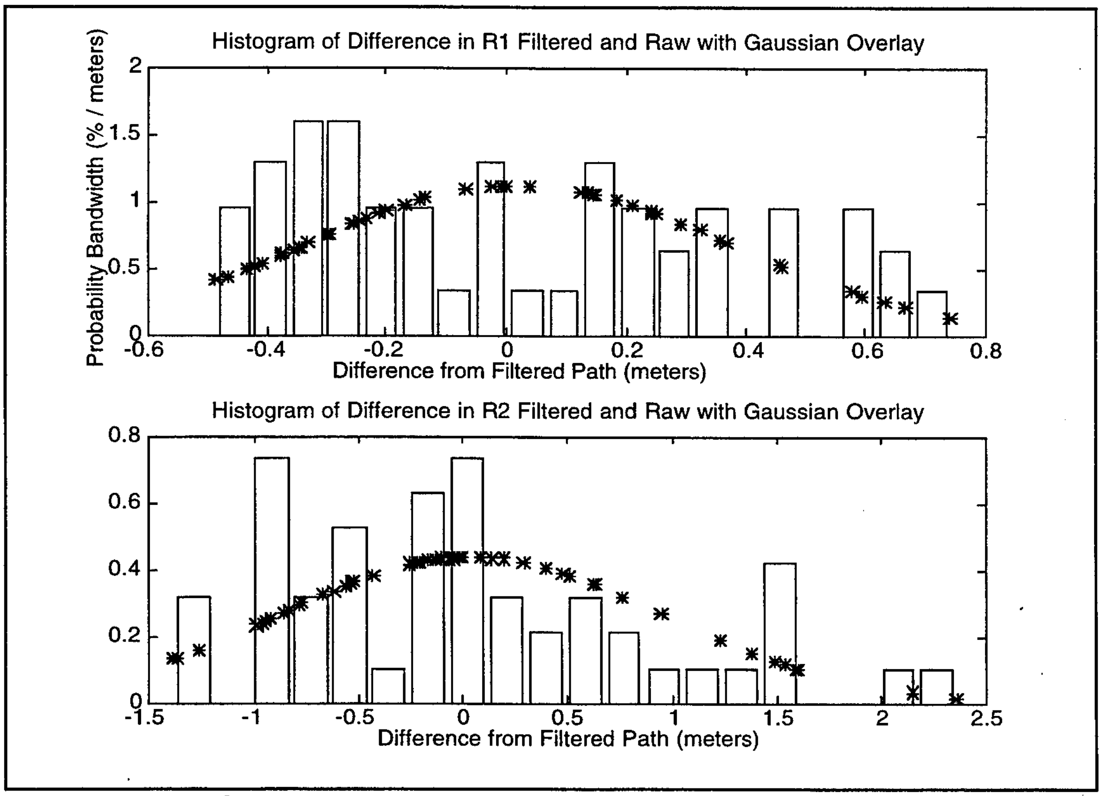

Figure 14 Run 2-01-7 Range Histograms

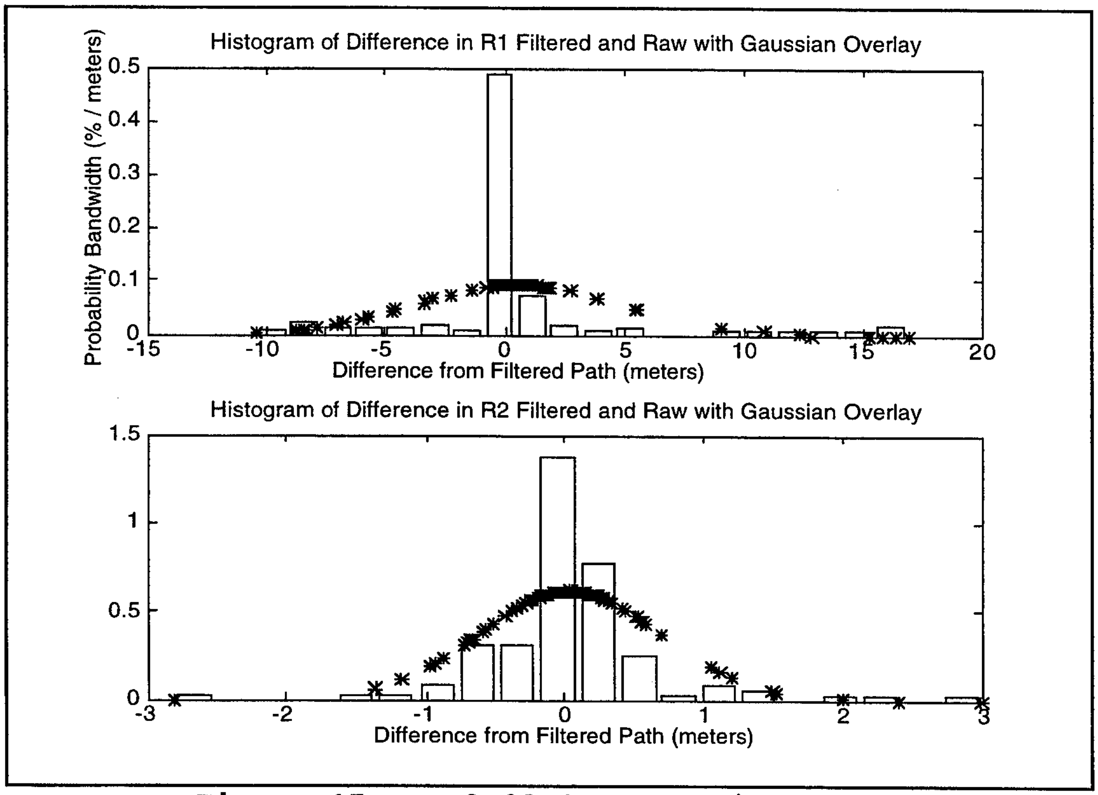

Figure 15 Run 2-02-1 Range Histograms

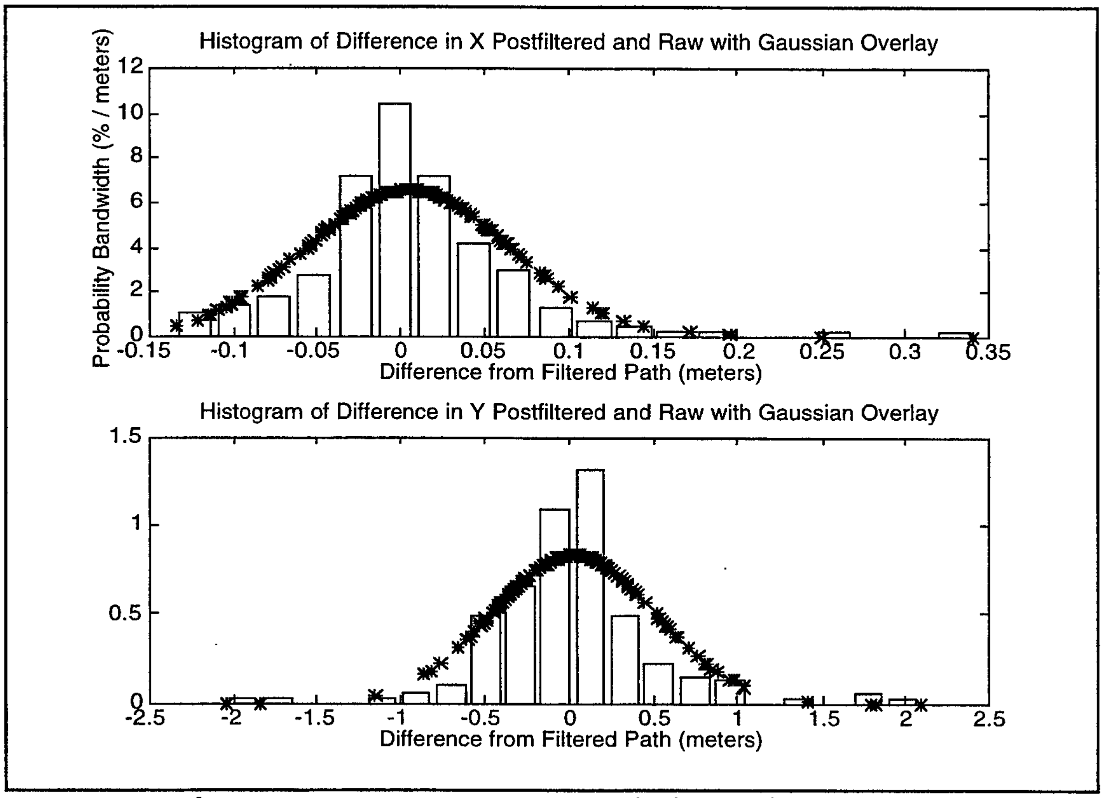

Figure 16 Run 2-01-2 Position Histograms

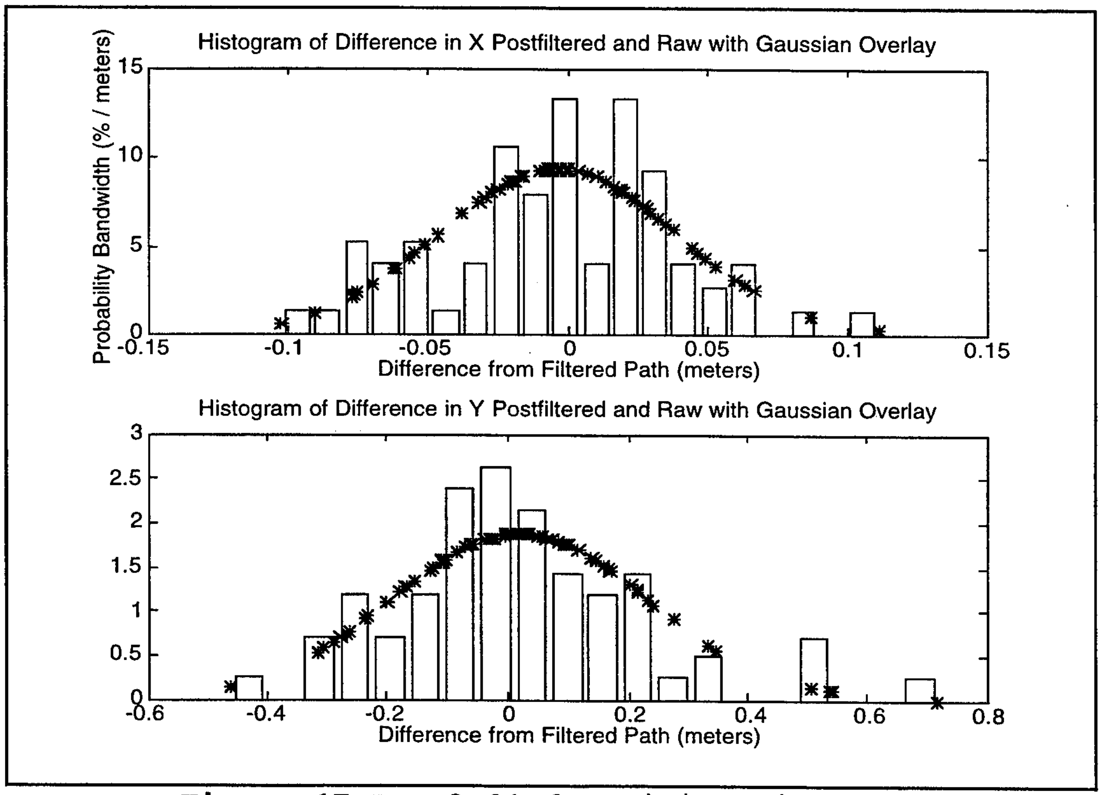

Figure 17 Run 2-01-6 Position Histogram

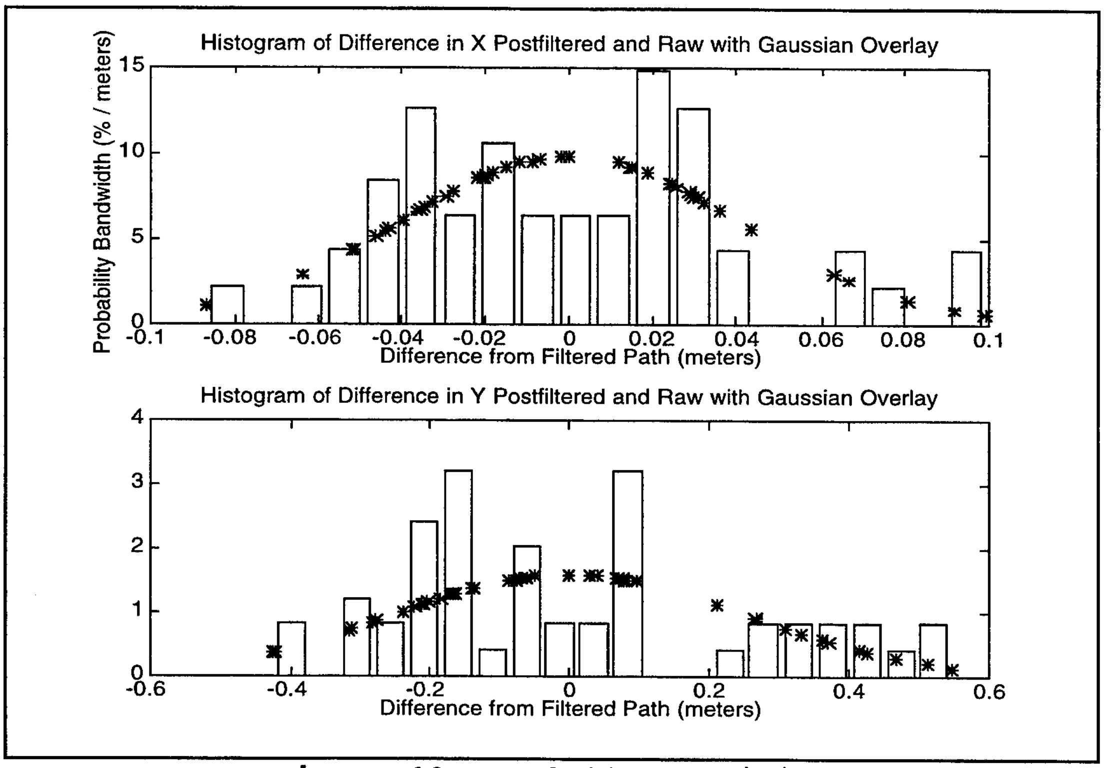

Figure 18 Run 2-01-7 Position Histograms

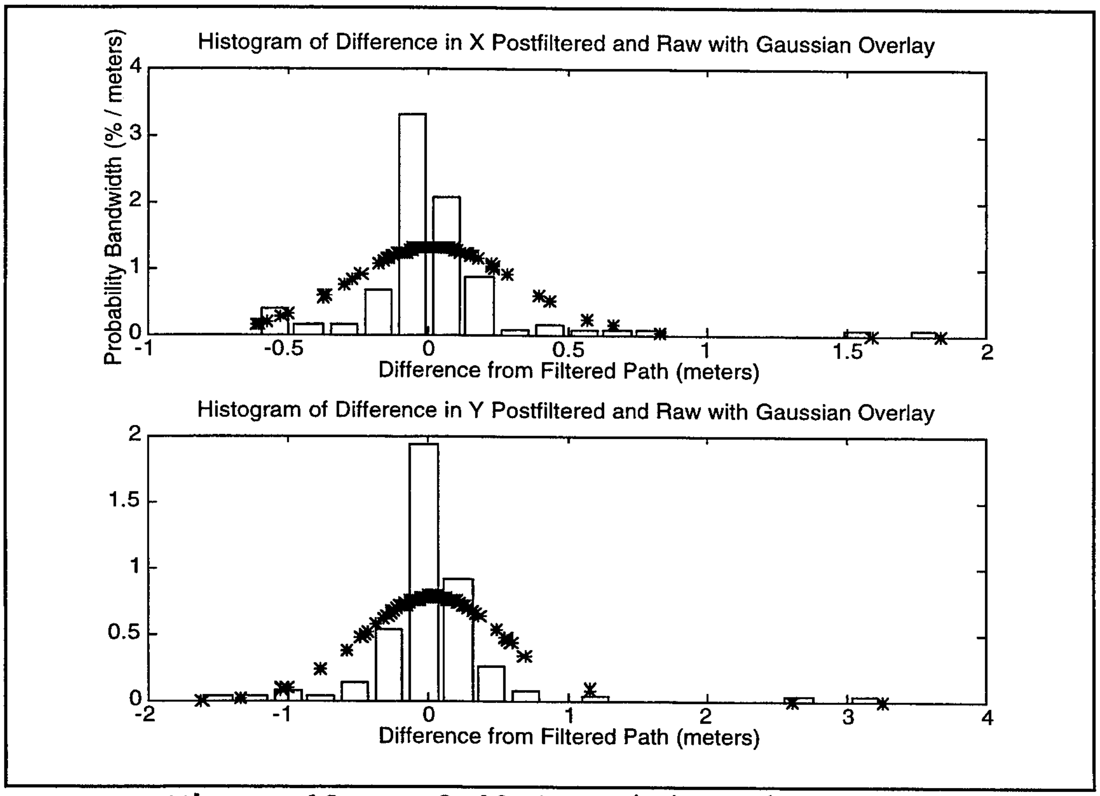

Figure 19 Run 2-02-1 Position Histograms

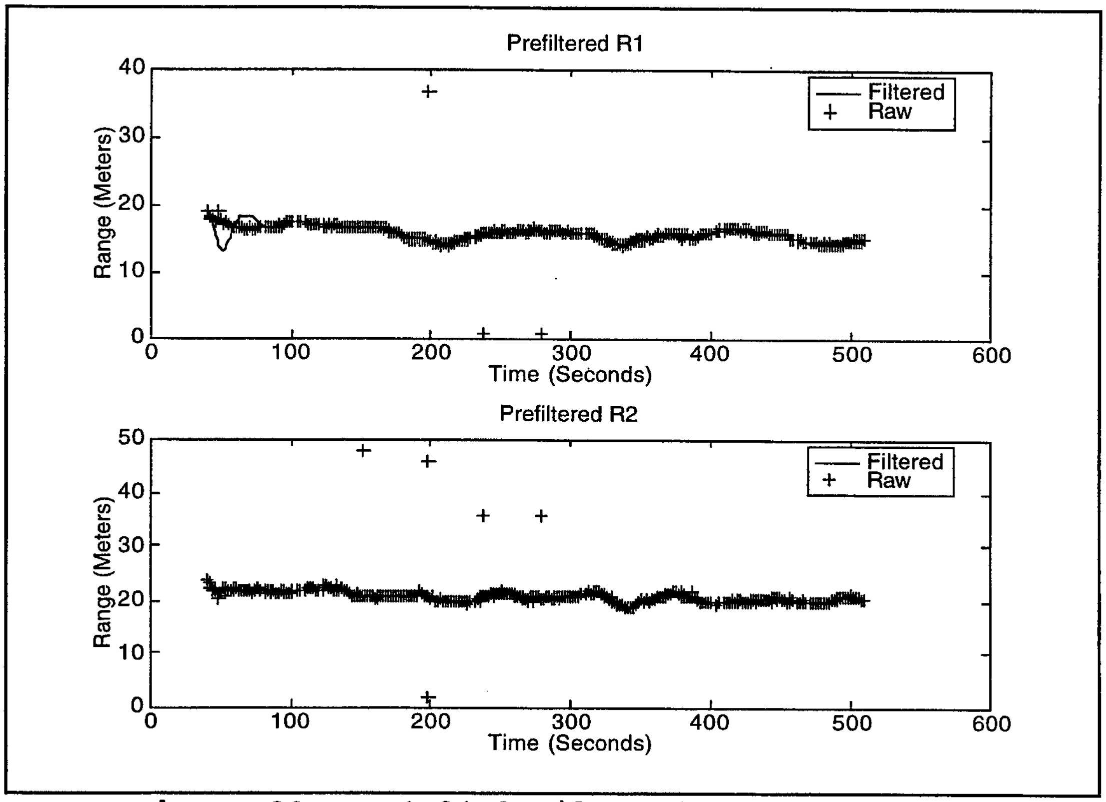

Figure 20 Run 1-31-3 Filtered and Raw Ranges

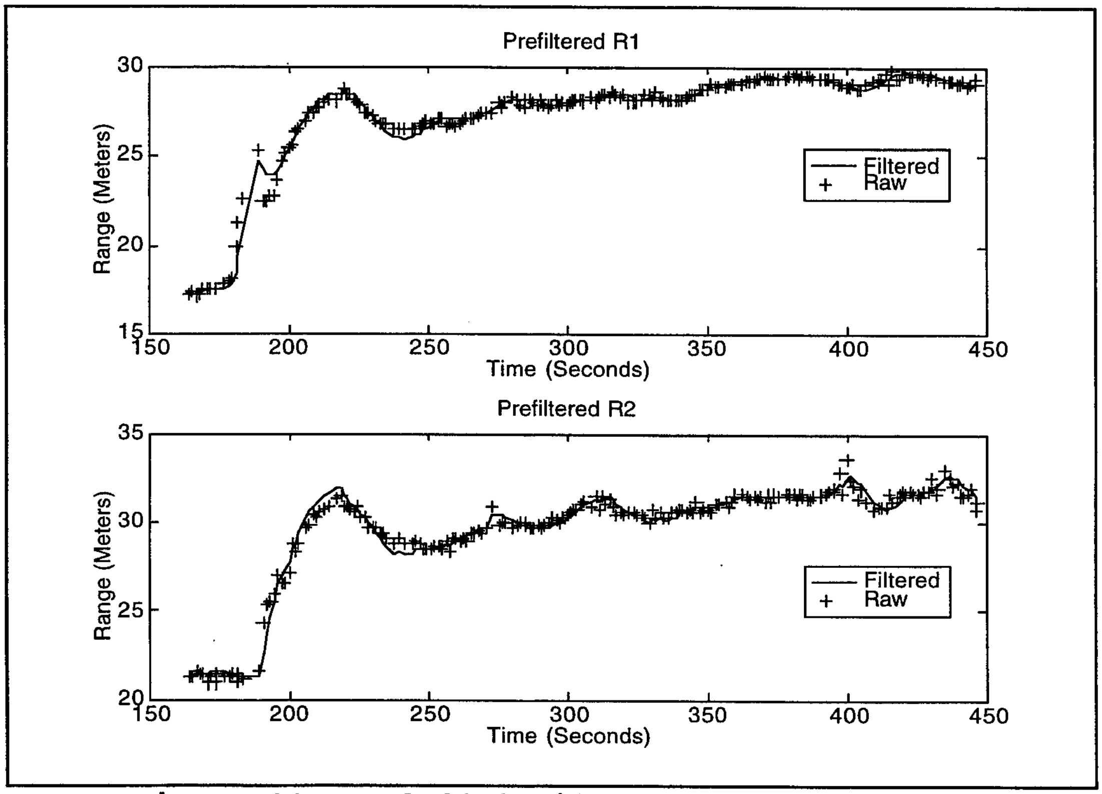

Figure 21 Run 2-01-2 Filtered and Raw Ranges

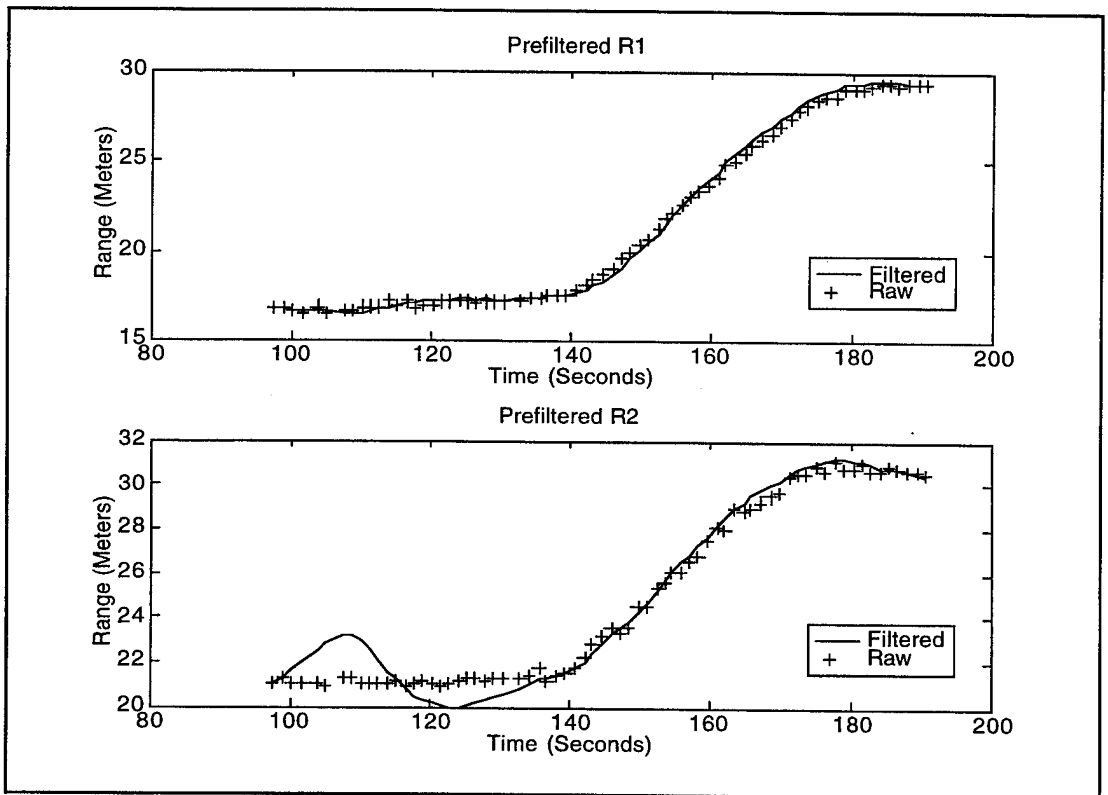

Figure 22 Run 2-01-6 Filtered and Raw Ranges

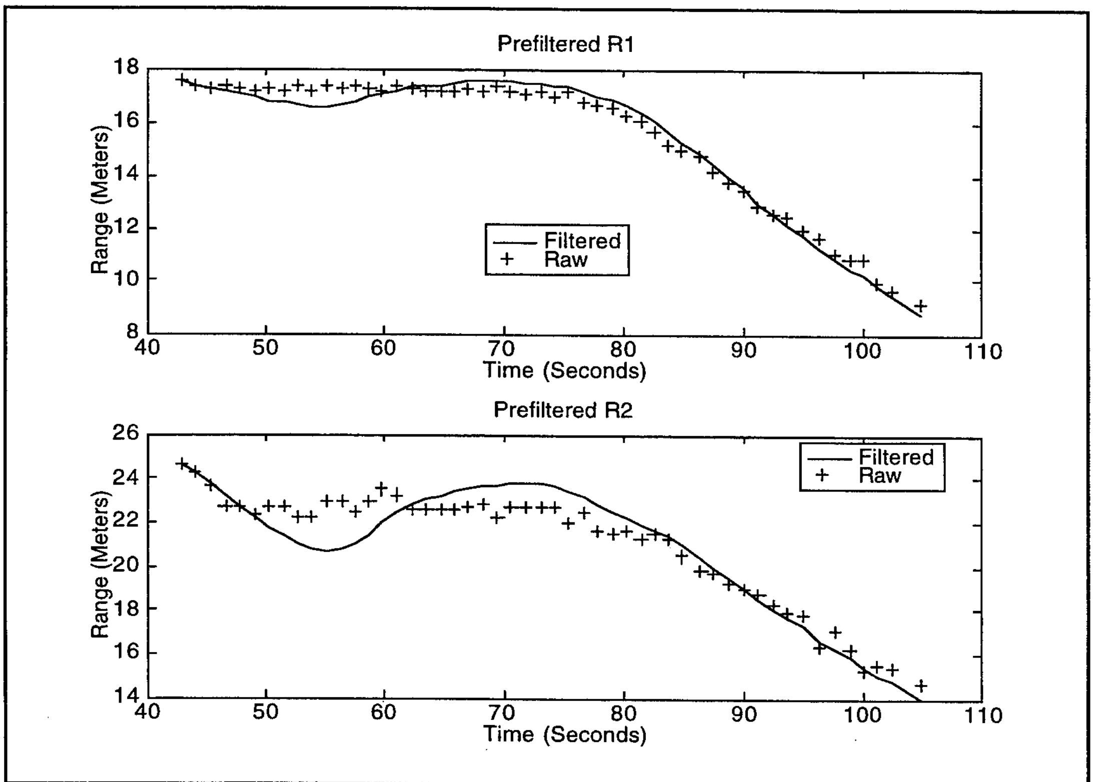

Figure 23 Run 2-01-7 Filtered and Raw Ranges

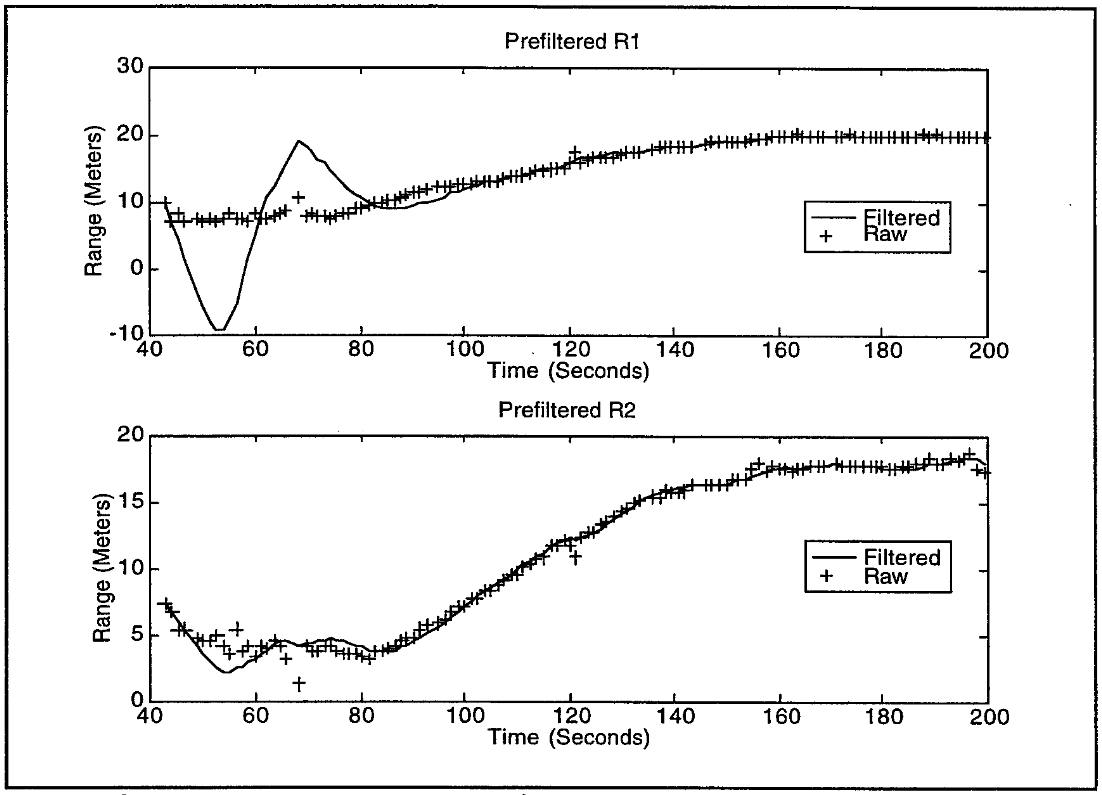

Figure 24 Run 2-02-1 Filtered Range vs Raw Range

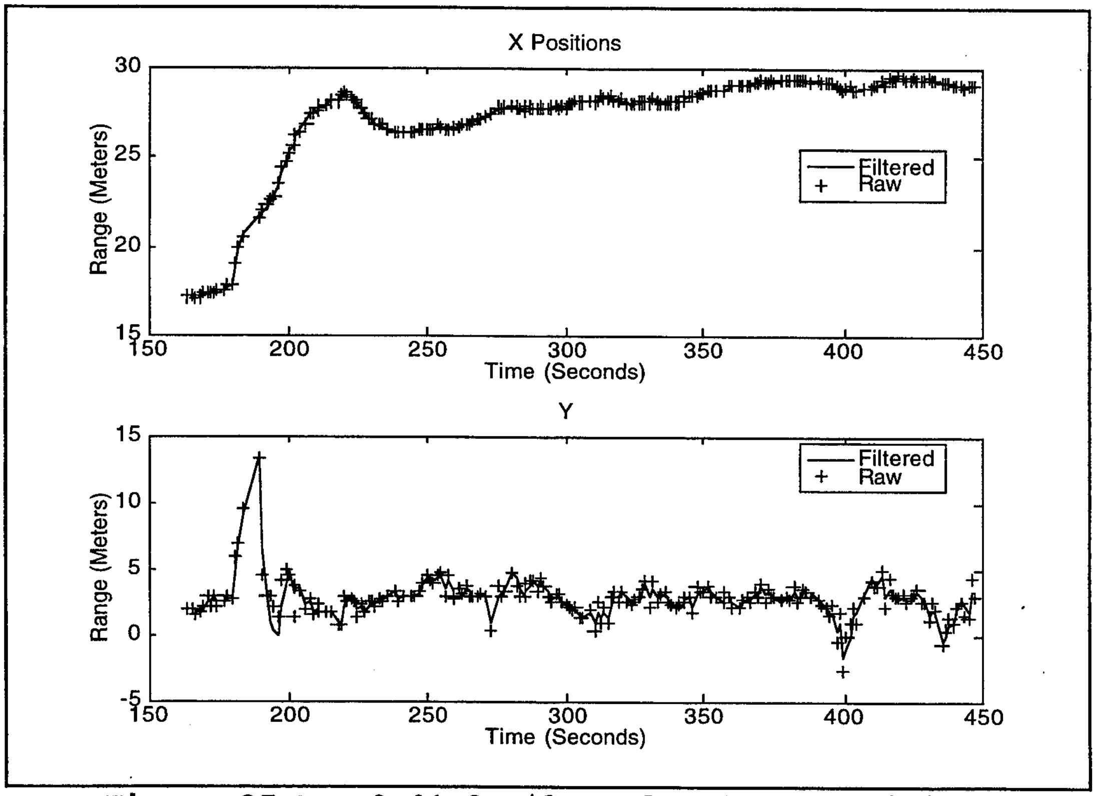

Figure 25 Run 2-01-2 Filtered and Raw Positions

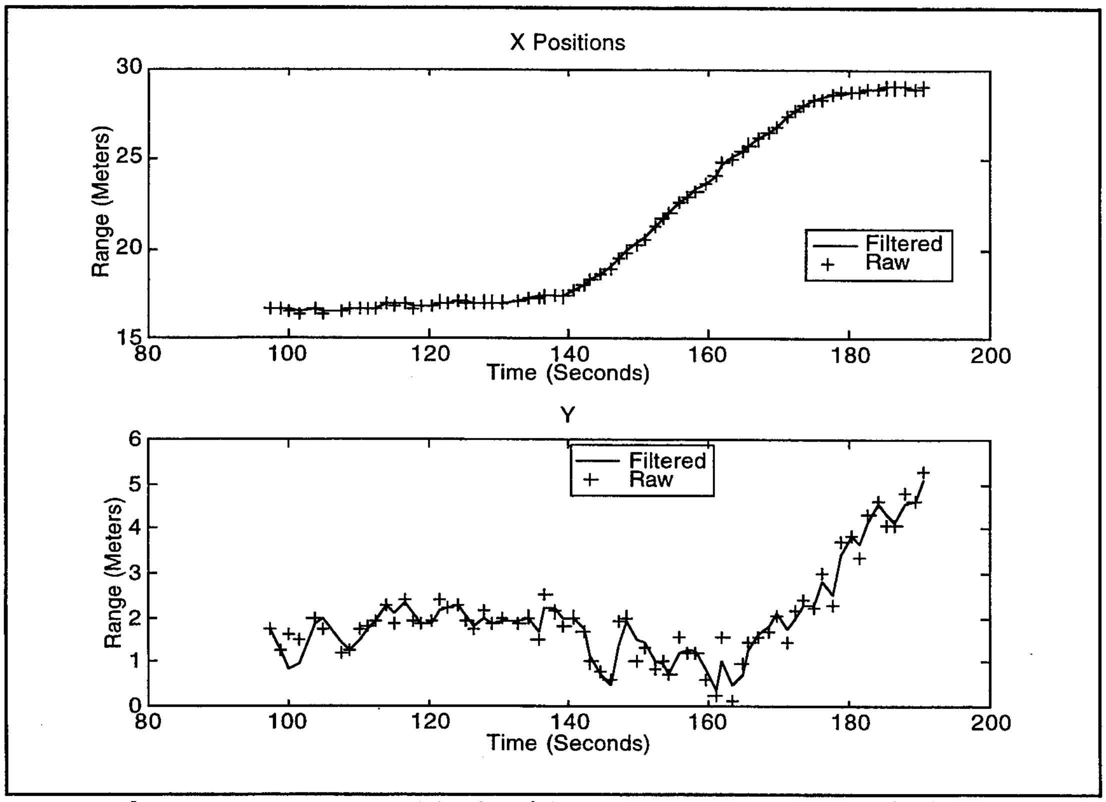

Figure 26 Run 2-01-6 Filtered and Raw Positions

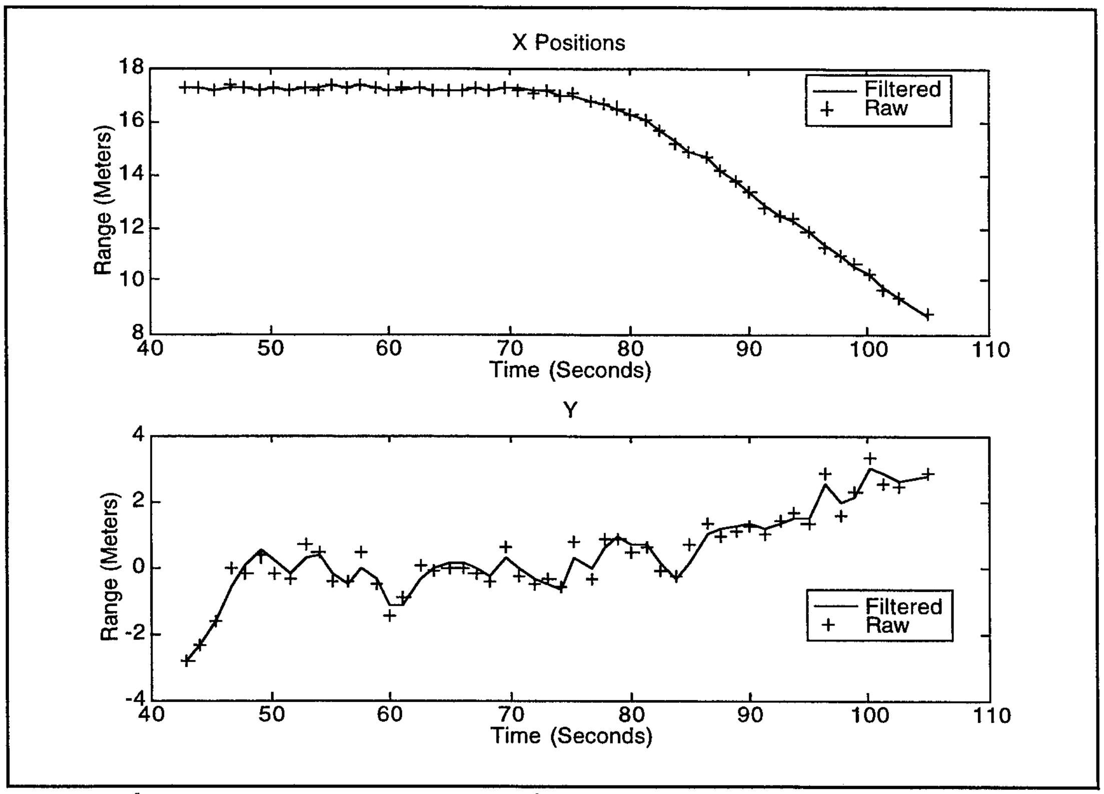

Figure 27 Run 2-01-7 Filtered and Raw Positions

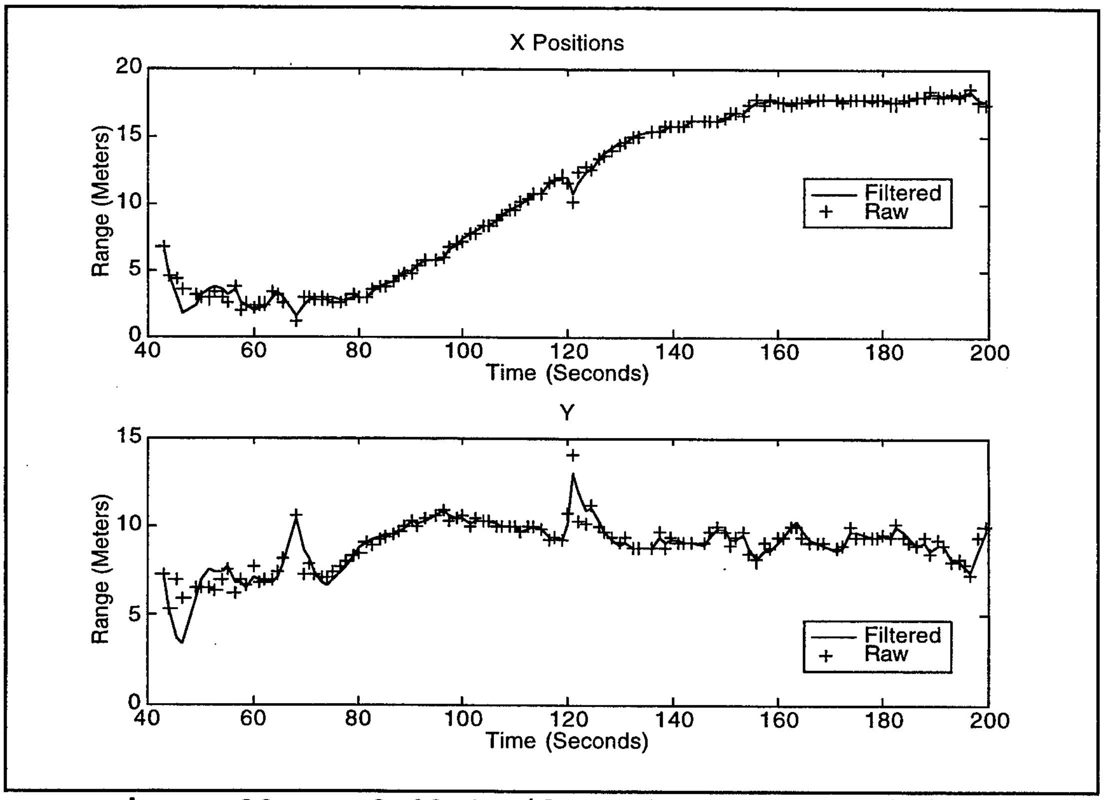

Figure 28 Run 2-02-1 Filtered and Raw Positions

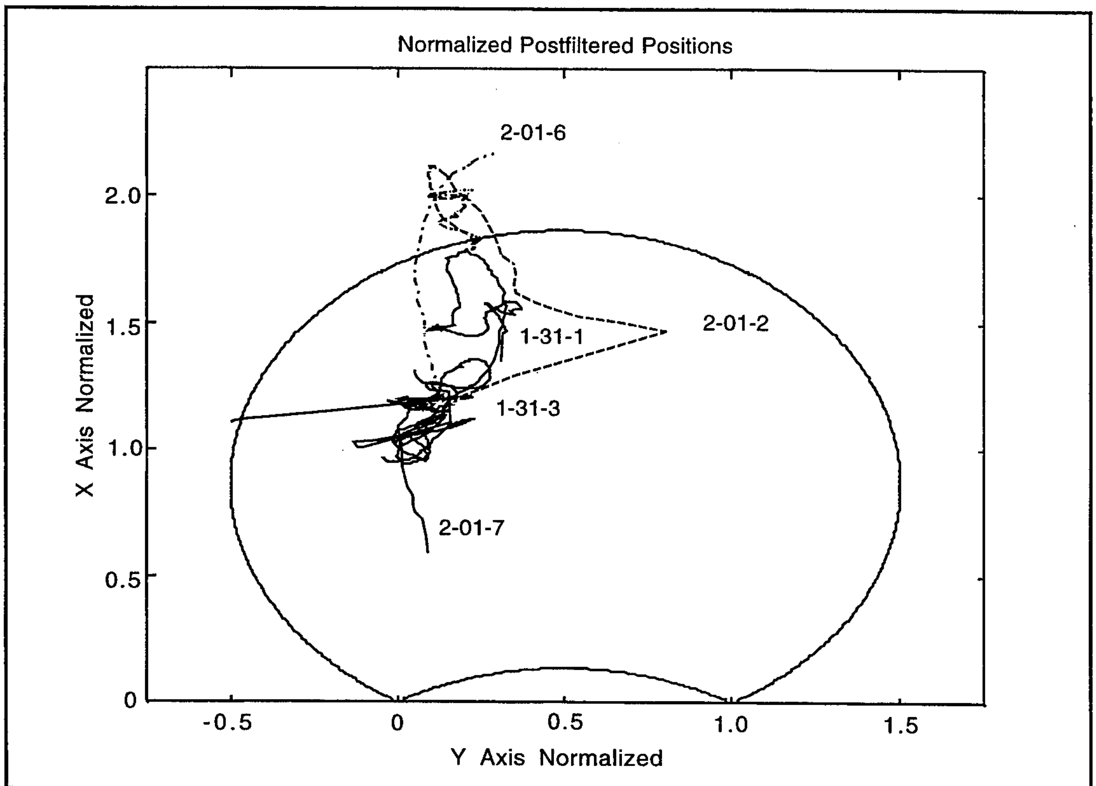

Figure 29 Normalized Post-Filtered Positions w/ 30° Tangent Loci

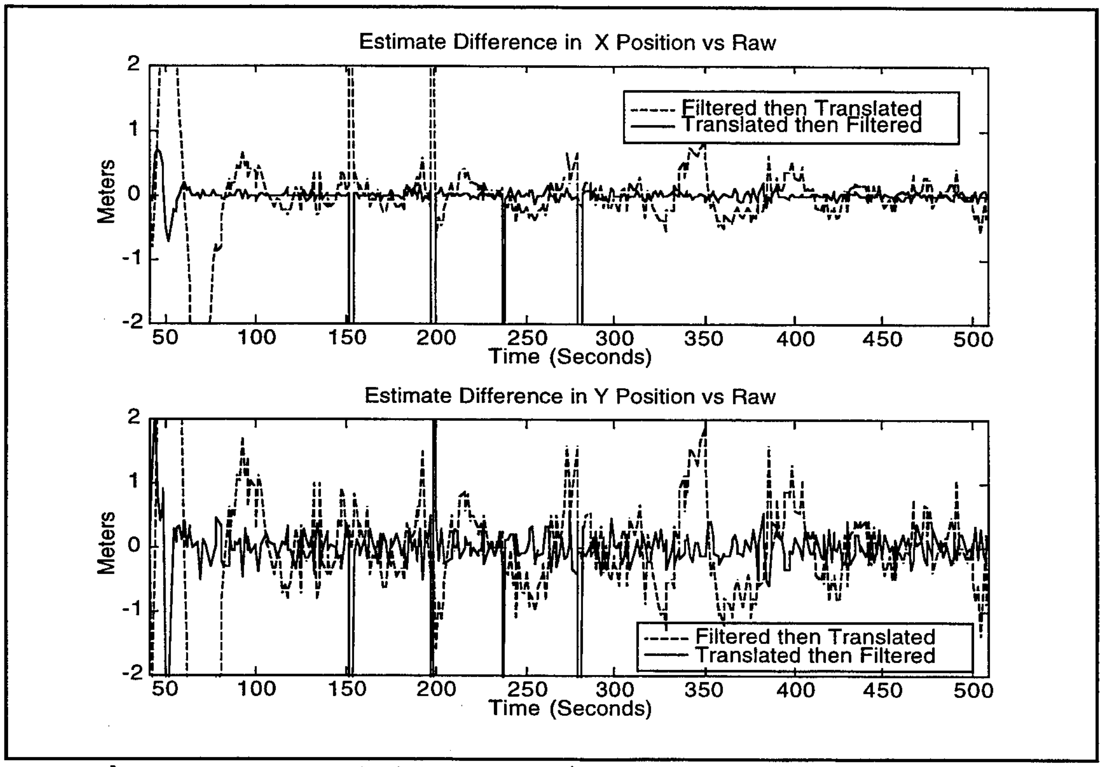

Figure 30 Run 1-31-3 Prefiltered and Postfiltered Position Difference

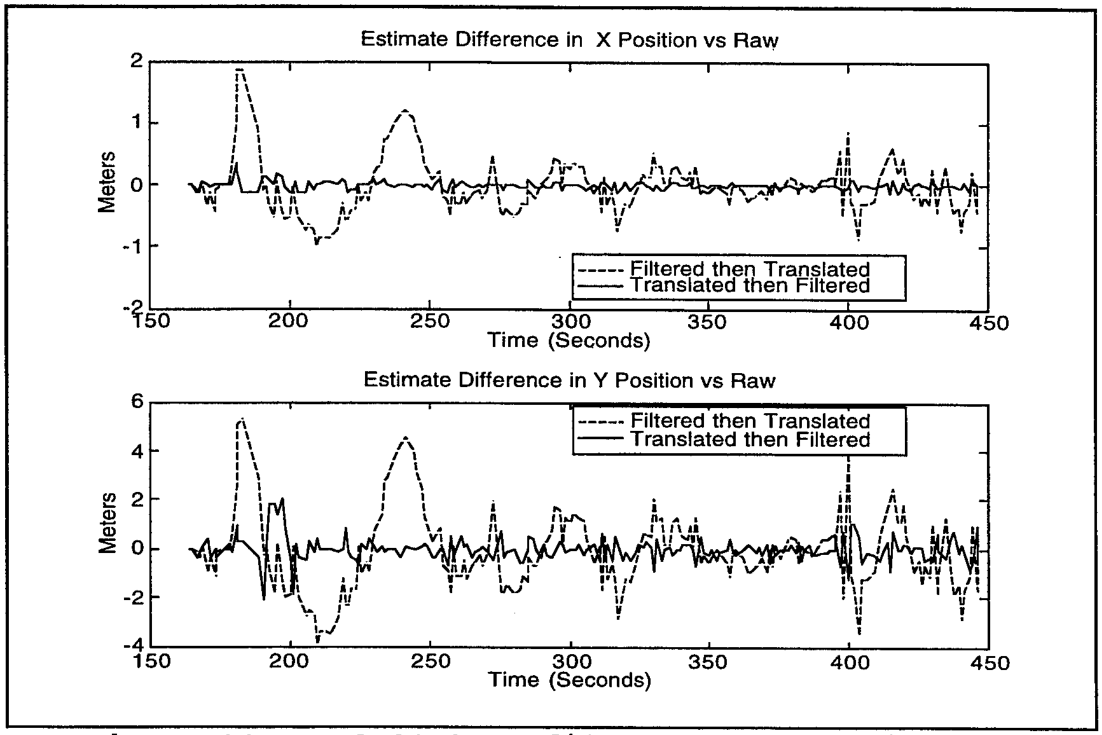

Figure 31 Run 2-01-2 Prefiltered and Postfiltered Position Difference

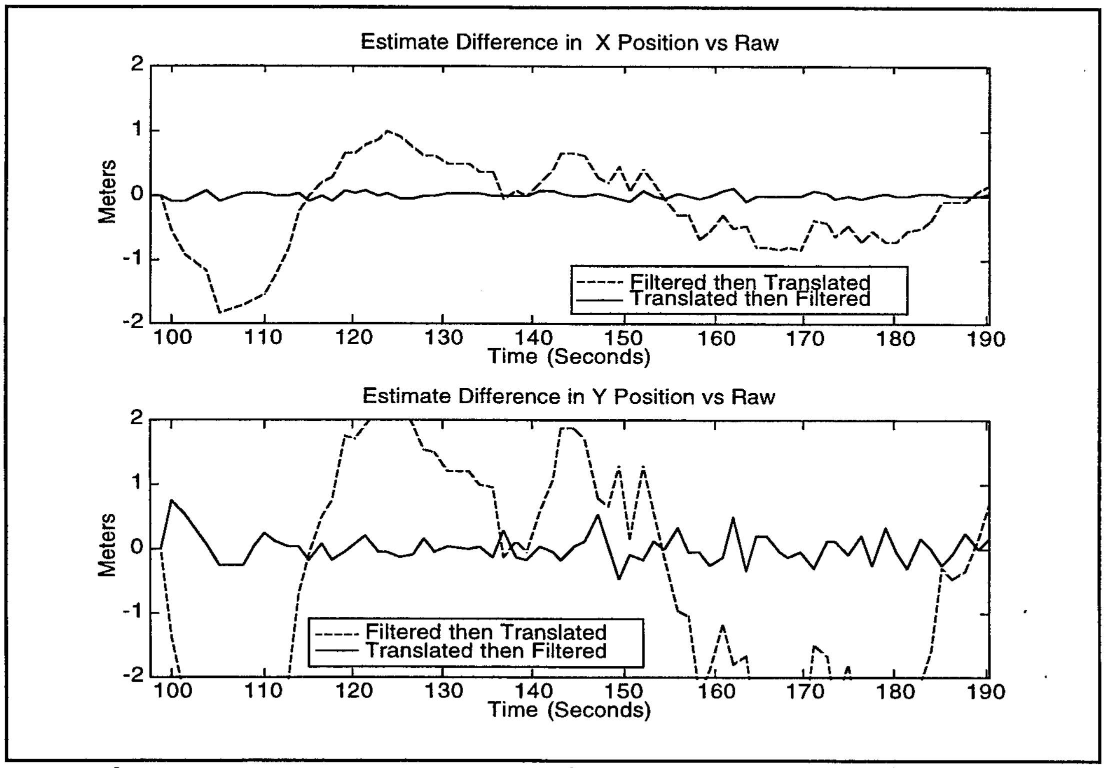

Figure 32 Run 2-01-6 Prefiltered and Postfiltered Position Difference

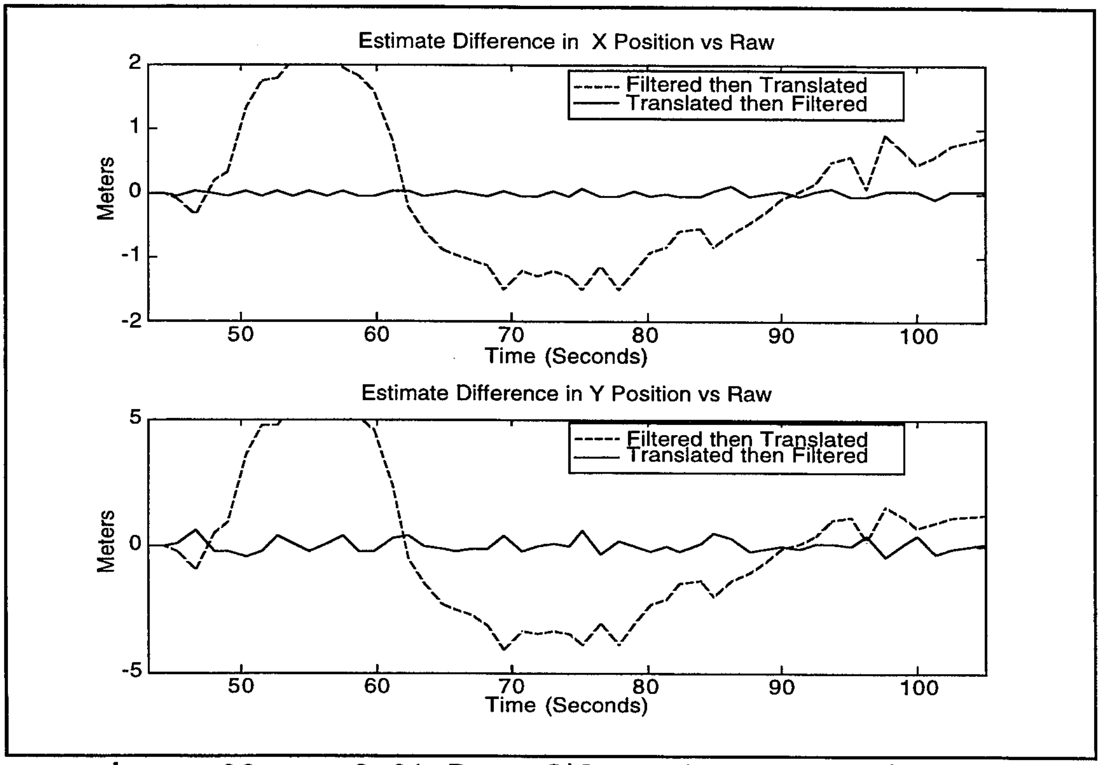

Figure 33 Run 2-01-7 Prefiltered and Postfiltered Position Difference

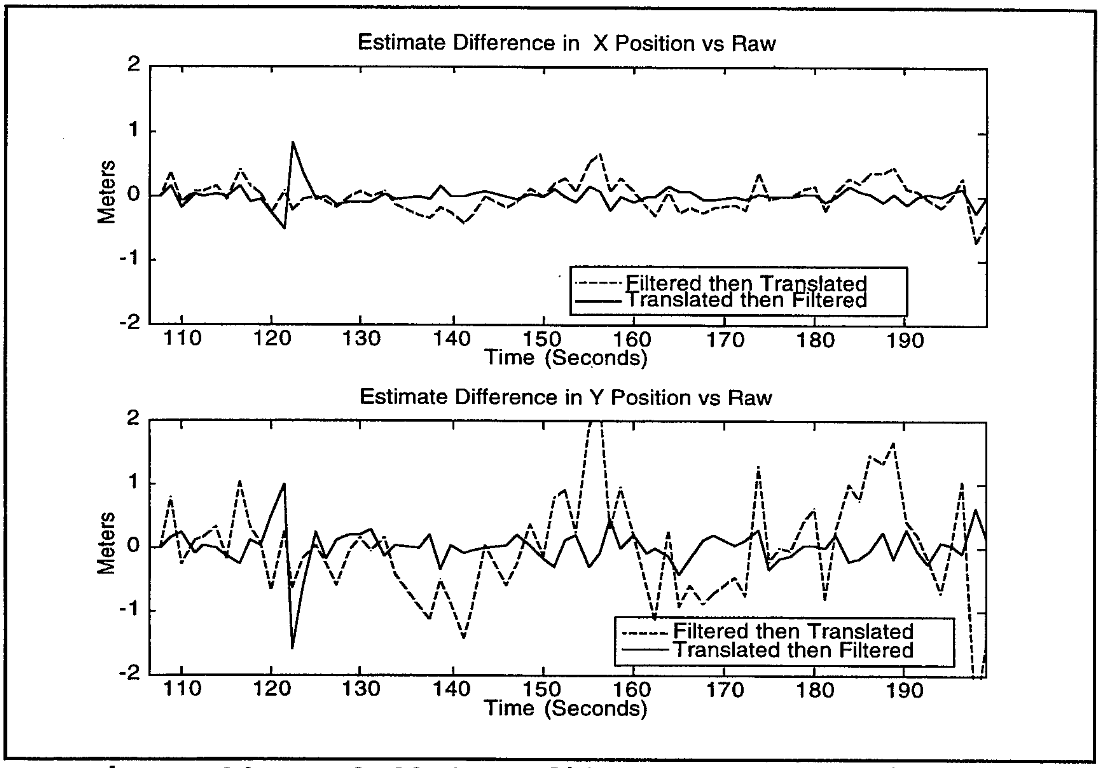

Figure 34 Run 2-02-1 Prefiltered and Postfiltered Position Difference

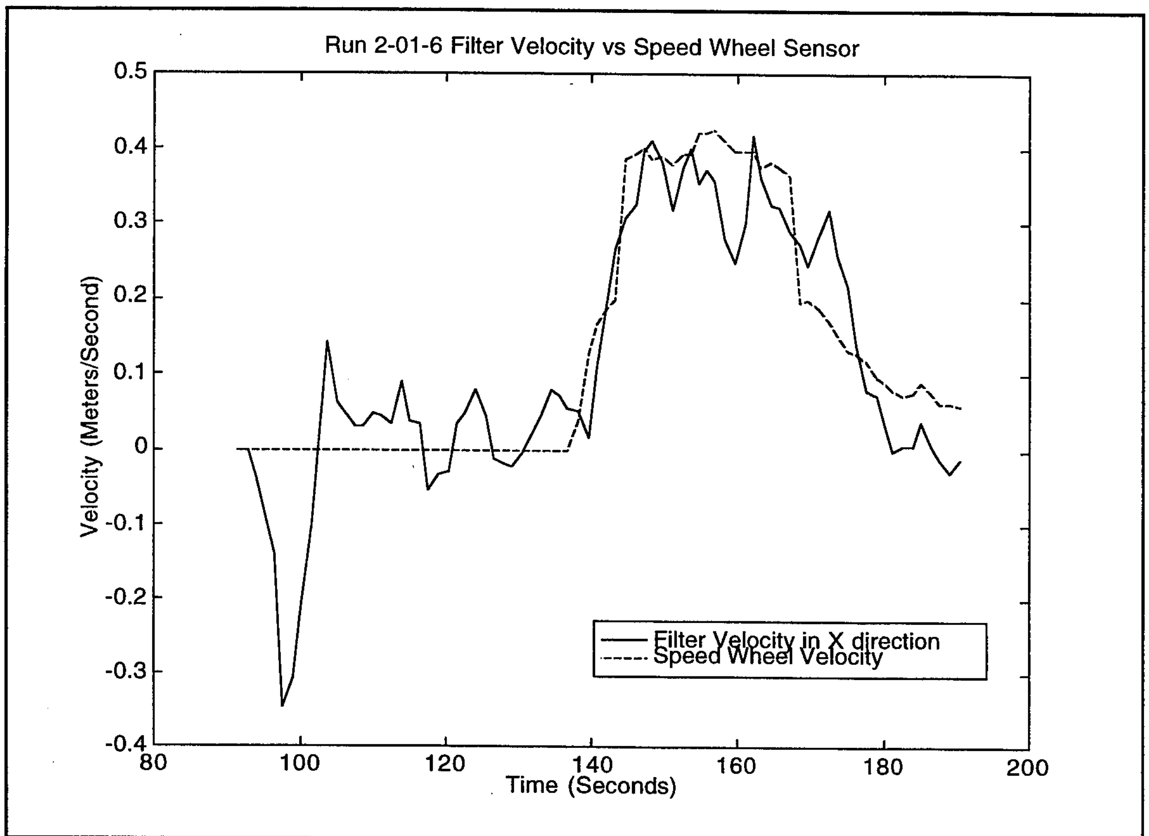

Figure 35 Run 2-01-6 Filtered X Velocity vs Speed Wheel Sensed Velocity

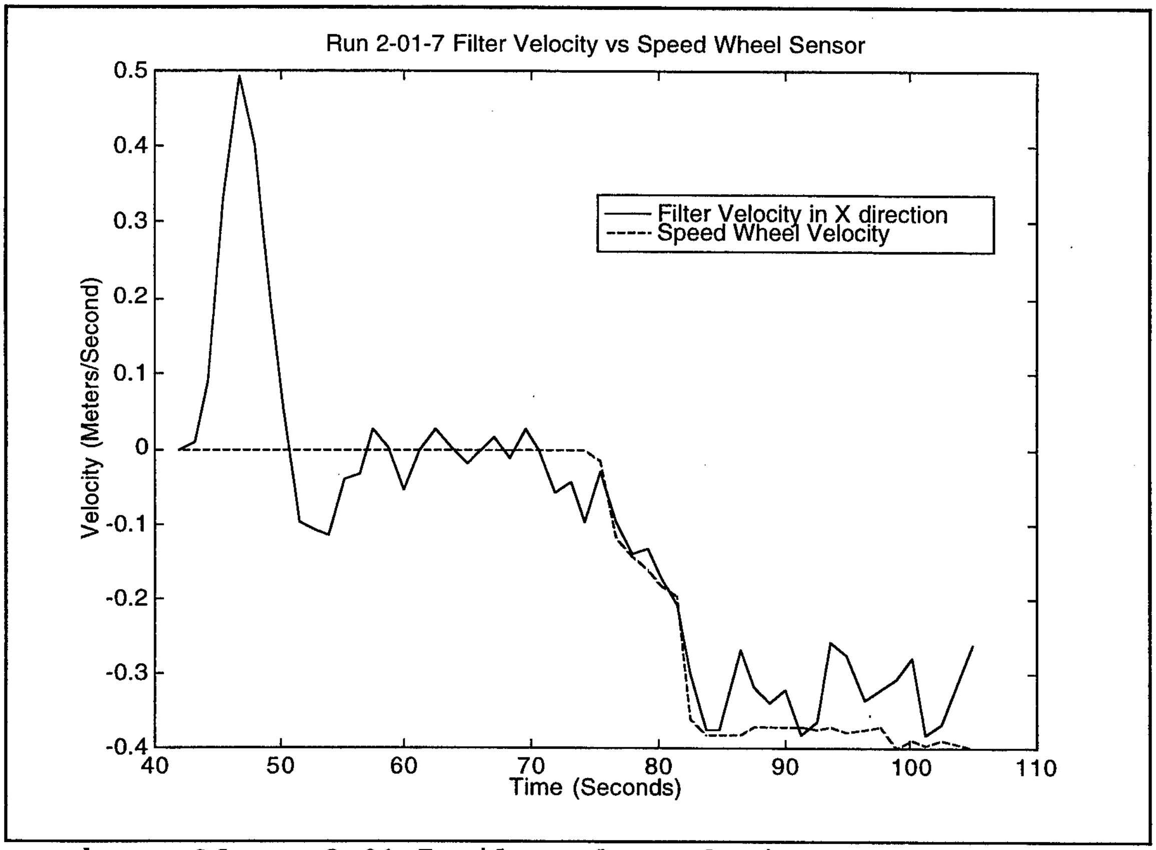

Figure 36 Run 2-01-7 Filtered X Velocity vs Speed Wheel Sensed Velocity

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

It has been clearly demonstrated that the DiveTracker system can be integrated with the Phoenix AUV for precise lateral positions. Raw range data should be translated into X and Y coordinates, then processed through a Kalman filter (postfiltering). The alternate method of filtering raw ranges first then converting into X and Y coordinates (prefiltering) results in amplification of Y position error.

B. RECOMMENDATIONS

It is recommended that the Phoenix AUV navigation process incorporate postfiltering of the X and Y position data to ensure precise lateral position.

Testing with a position reference available should be conducted to determine the optimal filter tuning and to determine if a constant gain observer could be used to condition DiveTracker navigation output.

Longer range testing of the Phoenix AUV should be conducted to determine if the DiveTracker errors are constant values or are the errors a function of range.

DiveTracker transducer should be remounted on the bottom of the Phoenix vehicle to allow for filter transients to subside during vehicle initialization.

Additional runs of extended time at speeds should be conducted to further correlate longitudinal speed sensor data with DiveTracker filter velocity to better set the speed sensor gain.

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2. Atkinson, R. Crusade, *The Untold Story of the Persian Gulf War*, New York, New York, pp. 321-330., 1993. *Commander, Mine Warfare Command*, 25 September 1995.

3. Borda, J. M. Admiral, Chief of Naval Operations, *Mine Countermeasures - An Integral Part of Our Strategy and Our Forces*, 13 December 1995.

4. COMMINEWARCOM JOINT COUNTERMINE ACTD PHASE III, *Report to Commander, Mine Warfare Command*, 25 September 1995.

5. *Desert Star Systems DiveTracker DTX User's Manual Second Edition*, October 1995.

6. Gebb, A., *Applied Optimal Estimation*, Cambridge, Massachusetts, pp 107-119, September 1974.

APPENDIX A: DIVEBASE.PAR

```
/*
 * DiveBase Default Mission Parameter File
 *
 * This file defines DiveBase operational parameters when
operating in
 * real-time mode or in replay mode when no mission specific
parameter file
 * is available.
 *
 * Each command must be preceded by the 'at' symbol and ends
at the end of
 * the line. (We can't print the 'at' symbol here, otherwise
what follows
 * would be interpreted as a command).
 *
 * Author:  Marco Flagg
 * Date:    April 30, 1995
 *
 * (C) 1994, Desert Star Systems
 *
 */


/*
 * Station ID list.
 * This list defines valid station ID codes and associates
them with a
 * station symbol and name.  The station symbol is used to
identify a
 * station on the dive site display.  The station name is
used for
 * identification in the various DiveBase data windows.
 * All stations must use the same station ID list to obtain
meaningful
 * communication.
 *
 * Command format: A<station ID>:<station symbol> <station
name>
 * where:
 * <station ID>:     00..49
 * <station symbol>: Up to three characters
 * <station name>:   Up to nine characters
 *
 */
@A00:S0 SURFACE-0
@A05:D0 PHOENIX

/*
 * Maximum AUV range (feet)
```

```
 */
@R: 1000


/*
 * Maximum baseline length (feet)
 */
@L: 100


/*
 * Communication speed:
 * 1. Speed:
 *      0: 3.6 nibbles/sec (14.2 baud)
 *      1: 8.9 nibbles/sec (35.7 baud)
 *      2: 17.9 nibbles/sec (71.4 baud)
 *      3: 35.7 nibbles/sec (142.8 baud)
 * 2. Receive<->Transmit Turn-around 'quiet' period: 0 -
999999 microseconds
 */
@S:1 125000


/*
 * Data exchange parameters:
 * 1. Receiver gain: 0 (least sensitive) - 3 (most sensitive)
 * 2. Detection threshold: 0 (most sensitive) - 127 (least
sensitive)
 * 3. Transmit power: 0 (least power) - 127 (most power)
 * 4. Pulse length: 0 - 9999 microseconds
 */
@X: 2 16 127 4000

/*
 * Distance measurement offset compensation (inch)
 * The indicated value is subtracted from any distance
measurement
 */
@C: 36

/*
 * Serial data transmission by diver or ROV/AUV station:
 * 1. Transmit 'raw' position data via serial link: 1=YES,
0=NO
 * 2. Transmit X-Y-Depth position data via serial link:
1=YES, 0=NO
 * 3. Transmit message data via serial link: 1=YES, 0=NO
@Z: 1 0 1


/*
```

```
 * Station function:
 * 0: Diver station
 * 1: Surface station
 * 2: Remote stations
 */
@F:0


/*
 * Station ID:
 * Surface station: 0
 * Remote stations: 0-3
 * Diver Stations:  0-9
 */
@I:0

/*
 * Network type & navigation protocol:
 * 1. Network type:
 *     0: Single transducer surface station only
 *     1: Dual transducer surface station
 *     2: Single transducer surface station & 1 remote station
 *     3: Single transducer surface station & 2 remote
stations
 *     4: Single transducer surface station & 3 remote
stations
 *     5: Single transducer surface station & 4 remote
stations
 * 2. Address mode:
 *     0: One diver station only (ping inquiry)
 *     1: More than one diver station (address code inquiry)
 * 3. Diver telemetry:
 *     0: Diver station sends no telemetry
 *     1: Diver station sends 2-channel telemetry (depth &
air)
 * 4. Navigation data availability:
 *     0: Navigation data is available to surface station only
 *     1: Navigation data is available to surface and diver
stations
 */
@N:1 0 0 1

/*
 * Number of divers to be inquired: 0-9
 */
@#:1


/*
 * Remote station locations (stations 0-3):
 * 1. Range (ft)
```

```
 * 2. Bearing (degrees)
 * 3. Depth (ft)
 *
 * note: Set all parameters to 0 for auto-survey
 */
@r0: 48 0 0
@r1: 0 0 0
@r2: 0 0 0
@r3: 0 0 0


/*
 * Operation side of baseline (used in network types 1 & 2):
 * 0: right
 * 1: left
 *
 */
@b:1


/*
 * Surface station transducer depth (feet)
 */
@d:0
```

END

APPENDIX B: KALMAN FILTER

```
function [xk]=highfilter1(in,Q,R,OL)
%    Matlab script to function as a Kalman Filter for
%         Range or Position information
%         Based on kalman filter provided by Dr. A. Healey
%         3 order model for relative motion
%         xdot = Ax + BQ
%         y = Cx + R
%
%         Variables:
%         in = Input matrix of Time vector and Range or
Position %         Vector
%         t =  Time vector
%         y =  Range or Position vector
%         A,B = Continuous Plant Model
%         xk = estimate of state vector
%         phi, gam = Discrete Plant Model
%    Q =  system noise variance
%         R =  measurement noise variance
%         pk = Covariance Matrix
%         pt = Updated estimate of the error covariances
%         OL = Outlier criteria
%         G =  Filter Gains
%         err =Innovation

t=in(:,1);
y=in(:,2);
A=[0, 1, 0; 0, 0, 1; 0, 0, 0];

B=[0;0;1];
C=[1,0,0];
D=0;

pk=diag([1e-1,1e-1,1e-1]);
xk=zeros(3,size(t));
G=xk;
err=zeros(1,size(t));

xk(1,1)=y(1);  % Set initial Range to First data point
xk(2,1) = (y(2)-y(1)/(t(2)-t(1))     % Set initial Velocity

%    For loop to solve for each time step

for i=2:size(t);
     dt=t(i)-t(i-1); % Determine time step for each interval
     [phi,gam]=c2d(A,B,dt);    % Calculate new for each time
step
     xk1=phi*xk(:,I-1);         % Estimate of state
     pt=phi*pk*phi'+gam*Q*gam';     % Propagate Std
Deviations
```

```
          G(:,I)=[pt*C'*inv(C*pt*C'+R)]; % Calculate Gains
     err(I)=[y(I)-C*xk1]; % Determine Innovation

%         Outlier Rejection

     if abs(err(i)) > OL  % Outlier criteria
          err(i)= 0;             % Ignore update due to
outlying data
     end                         % Ends if loop

     xk(:,i)=xk1+G(:,I)*err(I);      % Update estimate of
state
%
     pk=[eye(3)-G(:,I)*C]*pt;  % Update covariance matrix
     psave(1,I)=pk(1);                % Save covariance values
     psave(2,i)=pk(2);
     psave(3,i)=pk(3);
end       %    Ends for loop
```

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